NASA TECHNICAL MEMORANDUM

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NASA TM X- 73956-4

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LaRC DESIGN ANALYSIS REPORT

FOR

NATIONAL TRANSONIC FACILITY

FOR

9% NICKEL TUNNEL SHELL

THERMAL ANALYSIS

VOL. 4

BY

JAMES W. RAMSEY, JR., JOHN T. TAYLOR, JOHN F. WILSON,
CARL E. GRAY, JR., ANNE D. LEATHERMAN, JAMES R. ROOKER,
AND JOHNNY W. ALLRED

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Hampton, Virginia 23665

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16. Abstract This report contains the results of extensive computer (finite element, finite difference and numerical integration), thermal, fatigue, and special analyses of critical portions of a large pressurized, cryogenic wind tunnel (National Transonic Facility). The computer models, loading and boundary conditions are described. Graphic capability was used to display model geometry, section properties, and stress results. A stress criteria is presented for evaluation of the results of the analyses. Thermal analyses were performed for major critical and typical areas. Fatigue analyses of the entire tunnel circuit is presented.

The major computer codes utilized are: SPAR - developed by Engineering Information Systems, Inc. under NASA Contracts NAS8-30536 and NAS1-13977; SALORS - developed by Langley Research Center and described in NASA TN D-7179; and SRA - developed by Structures Research Associates under NASA Contract NAS1-10091; "A General Transient Heat-Transfer Computer Program for Thermally Thick Walls" developed by Langley Research Center and described in NASA TM X-2058.

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NTF TUNNEL SHELL

NASA LaRC

THERMAL ANALYSIS

9% Ni

SEPTEMBER 1976

VOLUME 4

LaRC CALCULATIONS

FOR THE

NATIONAL TRANSONIC FACILITY

TUNNEL SHELL

DATE: SEPTEMBER, 1976

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This report is one volume of a Design Analysis Report prepared by LaRC on portions of the pressure shell for the National Transonic Facility. This report is to be used in conjunction with reports prepared under NASA Contract NAS1-13535(c) by the Ralph M. Parsons Company (Job Number 5409-3 dated September 1976) and Fluidyne Engineering Corporation (Job Number 1060 dated September 1976). The volumes prepared by LaRC are listed below:

1. Finite Difference Analysis of Cone/Cylinder (9% Ni), Vol. 1, NASA TM X73956-1.

2. Finite Element Analysis of Corners #3 and #4 (9% Ni), Vol. 2, NASA TM X73956-2.

3. Finite Element Analysis of Plenum Region Including Side Access Reinforcement, Side Access Door and Angle of Attack Penetration (9% Ni), Vol. 3, NASA TM X73956-3.

4. Thermal Analysis (9% Ni), Vol. 4, NASA TM X73956-4.

5. Finite Element and Numerical Integration Analyses of the Bulkhead Region (9% Ni), Vol. 5, NASA TM X73956-5.

6. Fatigue Analysis (9% Ni), Vol. 6, NASA TM X73956-6.

7. Special Studies (9% Ni), Vol. 7, NASA TM X73956-7.

NTF DESIGN CRITERIA
FOR 9% NICKEL

GENERAL

THE DESIGN OF THE PRESSURE SHELL REFLECTED IN THIS REPORT SATISFIES THE DESIGN REQUIREMENTS OF THE ASME BOILER AND PRESSURE VESSEL CODE, SECTION VIII, DIVISION 1. SINCE DIVISION 1 DOES NOT CONTAIN RULES TO COVER ALL DETAILS OF DESIGN, ADDITIONAL ANALYSES WERE PERFORMED IN AREAS HAVING COMPLEX CONFIGURATIONS SUCH AS THE CONE CYLINDER JUNCTIONS, THE GATE VALVE BULKHEADS, THE BULKHEAD-SHELL ATTACHMENTS, THE PLENUM ACCESS DOORS AND REINFORCEMENT AREAS, THE ELLIPTICAL CORNER SECTIONS, AND THE FIXED REGION (RING S8) OF THE TUNNEL. THE DIVISION 1 DESIGN CALCULATIONS, THE ADDITIONAL ANALYSES AND THE CRITERIA FOR EVALUATION OF THE RESULTS OF THE ADDITIONAL ANALYSES TO ENSURE COMPLIANCE WITH THE INTENT OF DIVISION 1 REQUIREMENTS ARE CONTAINED IN THE TEXT OF THIS REPORT. THE DESIGN ANALYSES AND ASSOCIATED CRITERIA CONSIDERED BOTH THE OPERATING AND HYDROSTATIC TEST CONDITIONS.

IN CONJUNCTION WITH THE DESIGN, A DETAILED FATIGUE ANALYSIS OF THE PRESSURE SHELL WAS ALSO PERFORMED UTILIZING THE METHODS OF THE ASME CODE, SECTION VIII, DIVISION 2.

MATERIAL

THE PRESSURE SHELL MATERIAL SHALL BE ASME, SA-553-1 FOR PLATE AND SA-522 FOR FORGINGS. THE MATERIAL PROPERTIES AT TEMPERATURES EQUAL TO OR BELOW 150°F ARE AS FOLLOWS:

(A) PLATE, 2.0 INCHES OR THINNER

YIELD = 85.0 KSI
ULTIMATE = 100 KSI

(B) WELDS (AUTOMATIC AND SEMIAUTOMATIC)

YIELD = 52.5 KSI
ULTIMATE = 95.0 KSI

(C) WELDS (HAND)

YIELD = 58.5 KSI
ULTIMATE = 95.0 KSI

OPERATING, DESIGN AND TEST CONDITIONS

THE OPERATING, DESIGN AND TEST CONDITIONS FOR THE TUNNEL PRESSURE SHELL AND ASSOCIATED SYSTEMS AND ELEMENTS ARE SUMMARIZED BELOW:

1. OPERATING MEDIUM

   ANY MIXTURE OF AIR AND NITROGEN

2. DESIGN TEMPERATURE RANGE

   MINUS 320 DEGREES FAHRENHEIT TO PLUS 150 DEGREES FAHRENHEIT, EXCEPT IN THE REGION OF THE PLENUM BULKHEADS AND GATE VALVES INSIDE A 23-FOOT, 4-INCH DIAMETER, FOR WHICH THE TEMPERATURE RANGE IS MINUS 320 DEGREES FAHRENHEIT TO PLUS 200 DEGREES FAHRENHEIT.

3. PRESSURE RANGE

	TUNNEL CONFIGURATION	OPERATING PRESSURE RANGE, PSIA	DESIGN PRESSURES PSID
A.	CONDITION I - PLENUM ISOLATION GATES OPEN AND TUNNEL OPERATING:		
	TUNNEL CIRCUIT EXCEPT PLENUM	8.3 to 130	A. 8 EXTERNAL B. 119 INTERNAL
	PLENUM (PLENUM PRESSURE IS LIMITED TO .4 TO 1 TIMES THE REMAINDER OF THE TUNNEL CIRCUIT	3.3 to 130	A. 15 EXTERNAL B. 119 INTERNAL
	BULKHEAD		56 (EXTERNAL TO PLENUM)
B.	CONDITION II - PLENUM ISOLATION GATES OPEN AND TUNNEL SHUTDOWN:		
	ENTIRE TUNNEL CIRCUIT	8.3 to 130	A. 8 EXTERNAL B. 119 INTERNAL
	BULKHEAD		0

C. CONDITION III - PLENUM ISOLATION GATES AND ACCESS DOORS CLOSED:		
TUNNEL CIRCUIT EXCEPT PLENUM	8.3 to 130	A. 8 EXTERNAL B. 119 INTERNAL
PLENUM (PLENUM OPERATING PRESSURE CAN EXCEED THE PRESSURE IN THE REMAINDER OF THE TUNNEL CIRCUIT BY 24 PSI, BUT DOES NOT EXCEED THE 130 PSIA MAXIMUM OPERATING PRESSURE)	0 to 130	A. 15 EXTERNAL B. 119 INTERNAL
BULKHEAD		A. 25 (INTERNAL TO PLENUM) B. 119 (EXTERNAL TO PLENUM) FOR MINUS 320 DEGREES FAHRENHEIT TO PLUS 150 DEGREES FAHRENHEIT *C. 110.5 (EXTERNAL TO PLENUM) FOR PLUS 151 DEGREES FAHRENHEIT TO PLUS 200 DEGREES FAHRENHEIT

*OPERATING PROCEDURES LIMIT PRESSURES TO THAT SHOWN.

D. CONDITION IV - PLENUM ISOLATION GATES CLOSED AND ACCESS DOORS OPEN:		
TUNNEL CIRCUIT EXCEPT PLENUM	8.3 to 130	A. 8 EXTERNAL B. 119 INTERNAL
PLENUM	14.7	0
BULKHEAD		A. 119 (EXTERNAL TO PLENUM) FOR MINUS 320 DEGREES FAHRENHEIT TO PLUS 150 DEGREES FAHRENHEIT *B. 110.5 (EXTERNAL TO PLENUM) FOR PLUS 151 DEGREES FAHRENHEIT TO PLUS 200 DEGREES FAHRENHEIT

*OPERATING PROCEDURES LIMIT PRESSURES TO THAT SHOWN.

4. HYDROSTATIC TEST DESIGN CONDITIONS

THE PRESSURE SHELL WAS DESIGNED FOR HYDROSTATIC TEST IN ACCORDANCE WITH THE REQUIREMENTS OF THE ASME CODE, SECTION VIII, DIVISION 1. THE TEST PRESSURES SHALL BE AS FOLLOWS. PRESSURE SHELL TEMPERATURE SHALL BE EQUAL TO OR BELOW 100°F DURING HYDROSTATIC TESTS.

CONDITION (1) - MAXIMUM INTERNAL PRESSURE CONDITION FOR THE ENTIRE TUNNEL CIRCUIT

$$PH_1 = 1.5\ (119) + \text{HYDROSTATIC HEAD}$$
$$= 178.5\ \text{PSI} + \text{HYDROSTATIC HEAD}$$

CONDITION (2) - MAXIMUM DIFFERENTIAL PRESSURE CONDITION ACROSS THE PLENUM BULKHEADS

$$PH_2 = 1.5\ (119) + \text{HYDROSTATIC HEAD}$$
$$= 178.5 + \text{HYDROSTATIC HEAD}$$

$$PH_2{}^{*} = 1.5\ (111.5)\ \left(\frac{23.7}{22.2}\right) + \text{HYDROSTATIC HEAD}$$

$$= 178.5 + \text{HYDROSTATIC HEAD}$$

*TUNNEL OPERATION LIMITATIONS PRECLUDE PRESSURE DIFFERENTIALS ACROSS BULKHEADS IN EXCESS OF 110.5 PSI FOR BULKHEAD AND GATE TEMPERATURES IN EXCESS OF 150°F.

CONDITION (3) - MAXIMUM REVERSE DIFFERENTIAL PRESSURE CONDITION ACROSS THE PLENUM BULKHEADS

$$PH_3 = 1.5\ (25) = 37.5\ \text{PSI}$$

THE PRESSURE SHELL EXCEPT FOR THE PLENUM SHALL BE PRESSURIZED TO 141 PSIG. THE PLENUM SHALL BE PRESSURIZED TO 178.5 PSIG.

PRESSURE SHELL STRESS EVALUATION CRITERIA

THIS CRITERIA ESTABLISHES THE BASIS FOR ANALYSIS AND DESIGN OF THE PRESSURE SHELL SO IT WILL MEET OR EXCEED ALL OF THE REQUIREMENTS OF SECTION VIII, DIVISION 1 OF THE ASME BOILER AND PRESSURE VESSEL CODE AND CAN BE STAMPED WITH A DIVISION 1 "U" STAMP.

1. SECTION VIII, DIVISION 1, DIRECT APPLICATION

A. THE MAXIMUM ALLOWABLE STRESS (S)

S = 23.7 KSI (-320°F TO +150°F)

S = 22.2 KSI (-320°F TO +200°F)

(B) PRIMARY BENDING PLUS PRIMARY MEMBRANE STRESSES

THE LOCAL MEMBRANE STRESSES ARE NOT GENERALLY CONSIDERED IN SECTION VIII, DIVISION 1 DESIGNS. HOWEVER, FOR THE PURPOSE OF DESIGNING LOCAL REINFORCEMENT AT BRACKETS, RINGS OR PENETRATIONS NOT COVERED BY DESIGN BASED ON STRESS ANALYSIS, THE LOCAL SHELL MEMBRANE STRESS SHALL BE:

$$P_b + P_m \leq 1.5\ SE$$

NOTE: E IS JOINT EFFICIENCY

2. IN REGIONS OF THE PRESSURE SHELL WHERE DIVISION 1 DOES NOT CONTAIN RULES TO COVER ALL DETAILS OF DESIGN (REF. U-2(g)), ADDITIONAL ANALYSES WERE PERFORMED UTILIZING THE GUIDELINES OF THE ASME CODE, SECTION VIII, DIVISION 2, APPENDIX 4, "DESIGN BASED ON STRESS ANALYSIS." THE BASIC STRESS CRITERIA FOR DIVISION 2 IS REPRESENTED IN FIGURE 4-130.1 AND RESTATED BELOW INDICATING ANY MODIFICATIONS OR EXCESS REQUIREMENTS APPLIED TO IT TO REMAIN WITHIN THE INTENT OF DIVISION 1 AND TO OBTAIN A DIVISION 1 STAMP.

A. GENERAL PRINCIPAL MEMBRANE STRESS

MAXIMUM ALLOWABLE STRESS

S = 23.7 KSI (-320°F TO +150°F)

S = 22.2 KSI (-320°F TO +200°F)

MAXIMUM ALLOWABLE STRESS INTENSITY

S_m = 31.7 KSI (-320°F TO +200°F)

B. PRIMARY GENERAL MEMBRANE STRESS INTENSITY

$$P_m \leq S_m$$

AND IN ORDER TO COMPLY WITH DIVISION 1, THE MAXIMUM PRINCIPAL MEMBRANE STRESS MUST BE:

$$P_m^* \leq S$$

NOTE: THE * IS USED TO DENOTE THAT MAXIMUM PRINCIPAL STRESSES ARE TO BE COMPUTED FOR THE GIVEN LOADING CONDITION. THE INTENT IS TO DETERMINE THE STRESSES WHICH REPRESENT THE HOOP STRESSES AND MERIDIONAL STRESSES WHICH ARE THE STRESSES USED IN DIVISION 1 COMPUTATIONS.

C. DESIGN LOADS, PRIMARY LOCAL MEMBRANE STRESS INTENSITY

$$P_L \leq 1.5\ S_m$$

NOTE: LOCAL MEMBRANE STRESS INTENSITY IS DEFINED IN ACCORDANCE WITH DIVISION 2, APPENDIX 4-112(i). THE TOTAL MERIDIONAL LENGTH IS CONSIDERED TO BE 1.0 $\sqrt{RT}$.

D. DESIGN LOADS, PRIMARY LOCAL MEMBRANE PLUS PRIMARY BENDING STRESS INTENSITY

$$P_L + P_b \leq 1.5\ S_m$$

E. OPERATING LOADS, PRIMARY PLUS SECONDARY STRESS INTENSITY

$$P_L + P_b + Q \leq 3\ S_m$$

F. COMMENT

BECAUSE OF THE LOW YIELD STRENGTH EXPECTED AT THE WELDS AS COMPARED TO THE YIELD STRENGTH OF THE PLATE, STRESS INTENSITIES COMPUTED IN (A), (B), (C), (D), OR (E) SHALL NOT EXCEED THE YIELD STRENGTH OF THE MATERIAL AT EITHER WELD OR PLATE LOCATIONS.

3. A FATIGUE ANALYSIS WAS CONDUCTED IN ACCORDANCE WITH SECTION VIII, DIVISION 2 WITHOUT MODIFICATION.

4. HYDROSTATIC TEST CONDITION DESIGN CONSIDERATIONS

A. PRESSURE SHELL

IN ACCORDANCE WITH DIVISION 1 OF THE ASME CODE, DESIGN ANALYSIS OF THE PRESSURE SHELL FOR THE HYDROSTATIC TEST CONDITION IS NOT REQUIRED. HOWEVER, IN ORDER TO PROVIDE A SATISFACTORY ENGINEERING DESIGN FOR THE PRESSURE SHELL THE FOLLOWING CRITERIA WAS USED:

(a) THE MAXIMUM GENERAL MEMBRANE STRESS PERPENDICULAR TO A WELD LINE WAS LIMITED TO THE LESSER OF:

$$P_m* \leq 0.8 \text{ WELD YIELD STRESS}$$

OR

$$P_m* \leq 0.5 \text{ WELD ULTIMATE STRESS}$$

(b) THE GENERAL PRINCIPAL MEMBRANE STRESS IN THE PLATE (NOT AT A WELD) WAS LIMITED TO THE LESSER OF:

$P_m * \leq$ 0.8 PLATE YIELD STRESS

$P_m * \leq$ 0.5 PLATE ULTIMATE STRESS

(*) THE STRESSES SATISFYING THIS CRITERIA ARE BASED ON MAXIMUM MEMBRANE STRESSES RATHER THAN INTENSITY CRITERIA.

The enclosed analyses is for 9% Ni with a 6" of Temp-Mat Insulation with internal circumferential "T" rings. The new baseline insulation is a closed cell material "Rohacell", with internal tabs. The "Rohacell" insulation reduces the stresses contained herein by a factor of 10.

THERMAL ANALYSIS REPORT

BY______ DATE______ SUBJECT______ SHEET NO. 1 OF______
CHKD. BY______ DATE______ JOB NO.______

I STEADY STATE ANALYSIS OF BULKHEAD REGION.

COMPUTER PROGRAMS

1- TEMPERATURES WERE CALCULATED WITH "A GENERAL TRANSIENT HEAT-TRANSFER COMPUTER PROGRAM FOR THERMALLY THICK WALLS". NASA TECHNICAL MEMORANDUM NO. [TM X-2058]

16. Abstract

This program is a general heat-transfer program which employs a finite-difference method for the solution of temperature histories of one-dimensional, two-dimensional, or spherical systems. Options are available for heat input given in tabular form, computed from a trajectory, or computed from a temperature history given for a specific location. The types of heat exchange are: (1) conduction; (2) convection – with (a) given heat input, (b) heating due to skin friction with Van Driest equations, (c) stagnation heating with Sibulkin, Detra-Kemp-Riddell, and Cohen equations; (3) radiation-out; (4) air-conduction; and (5) joint conduction. The system configuration is specified by an arbitrary number of discrete elements and their interrelationships.

2- STRESSES WERE CALCULATED WITH "SPAR" WHICH IS A SYSTEM OF COMPUTER PROGRAMS USED PRIMARILY TO PERFORM STRESS, BUCKLING, AND VIBRATIONAL ANALYSES OF LINEAR FINITE ELEMENT SYSTEMS.

MANUAL NO. EISI/A2200 BY

ENGINEERING INFORMATION SYSTEM, INC.
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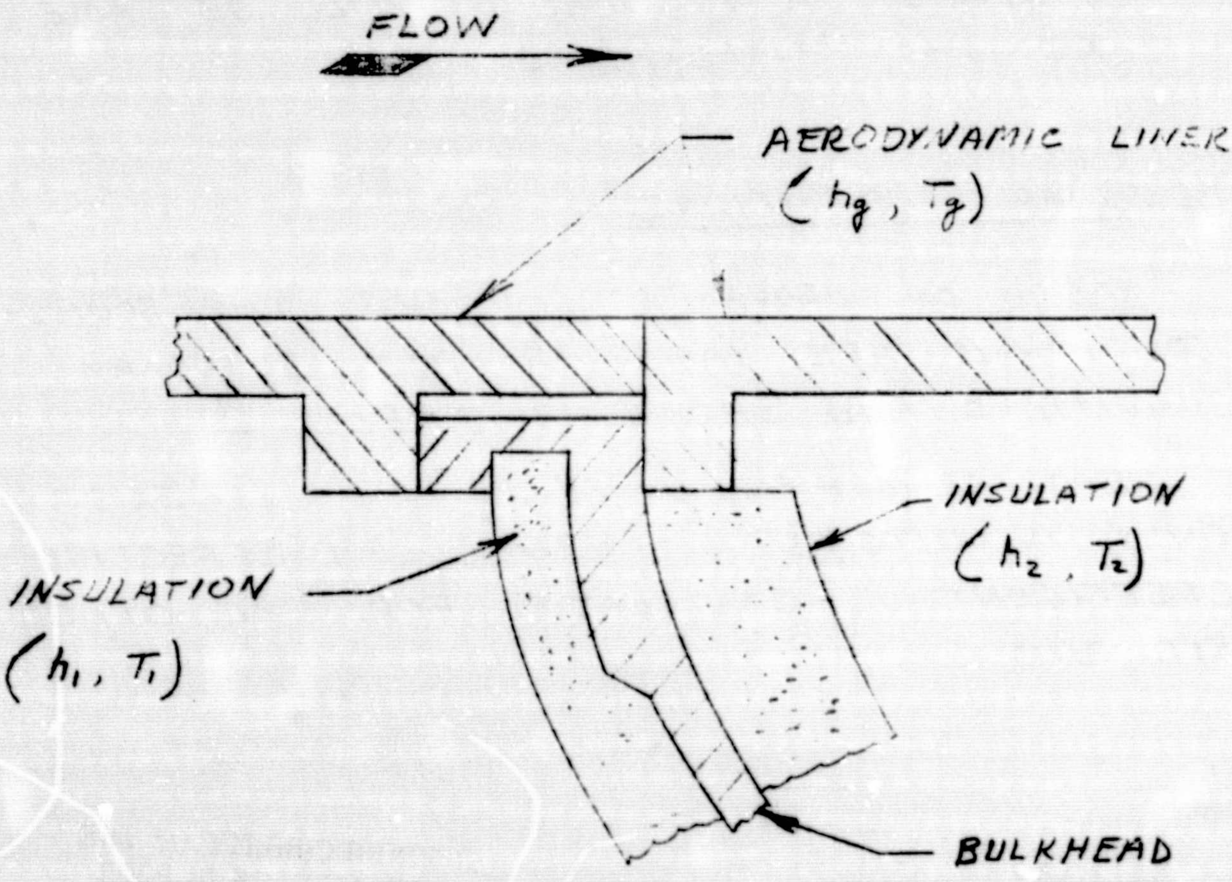
I- STEADY STATE ANALYSIS OF BULKHEAD

THE STEADY STATE THERMAL ANALYSIS OF THE BULKHEAD (DRAWING NO. HAS BEEN CONDUCTED FOR GATE VALVES OPENED AND CLOSED

A- GATE VALVE OPENED WITH FLOW:

THIS STEADY STATE CASE EXISTS WHEN THE TUNNEL IS IN OPERATION WITH THE AERO-DYNAMIC LINERS CONNECTED TO THE BUCKHEAD AS SHOWN BELOW



WHERE :

h = HEAT TRANSFER COEFFICIENT IN REGIONS SHOWN

T = TEMPERATURE OF GAS

ASSUMPTIONS:

1- ASSUME LINER TEMPERATURE TO EQUAL TO GAS STREAM TEMPERATURE SINCE FLOW IS NEAR MACH 1 AT LINER AND HEAT TRANSFER COEFFICIENT WILL BE LARGE.

2- ASSUME h_1 + h_2 ARE LARGE. THE RESISTANCE OF HEAT FLOW THRU SURFACE FILM WILL BE SMALL COMPARED TO RESISTANCE OF HEAT THRU INSULATION. THEREFORE OUTER SURFACE OF INSULATION WILL BE SAME AS GAS TEMPERATURE.

BOUNDARY CONDITIONS

BASED ON ABOVE ASSUMPTIONS, THE BOUNDARY CONDITIONS ARE SAME AS A/E BOUNDARY CONDITIONS AND SHOWN IN TABLE 1

HEAT TRANSFER COEFFICIENT WILL EXIST ONLY IN BLOCKS 1 THRU 6. AN EFFECTIVE COEFFICENT IS CALCULATED FOR THE OTHER ELEMENT.

EFFECTIVE THERMAL BOUNDARY CONDITION IS DETERMINED BY DIVIDING THE THERMAL CONDUCTIVITY BY THE INSULATION THICKNESS.

FOR EXAMPLE:

$$K = 1.47 \frac{Btu\text{-}IN}{FT^2\text{-}HR\text{-}°F}$$

$$t = 6 \text{ INCHES}$$

$$\therefore h_e = \frac{1.47 \frac{Btu\text{-}IN}{FT^2\text{-}HR\text{-}°F}}{6 \text{ IN}} = .245 \frac{Btu}{FT^2\text{-}HR\text{-}°F}$$

$$h_e = 4.726 \times 10^{-7} \frac{Btu}{IN^2\text{-}sec\text{-}°F}$$ ✓

GEOMETRY

THE DIMENSIONS OF THE FINITE ELEMENT MODEL IS SHOWN IN FIGURE 1

DETERMINATION OF HEAT TRANSFER COEFFICIENT AND GAS TEMPERATURE FOR COMPUTER PROGRAM.

THE COMPUTER PROGRAM WILL ALLOW ONLY ONE GAS HEAT TRANSFER COEFFICIENT AND ONE GAS TEMPERATURE FOR EACH ELEMENT. THEREFORE, THESE VALUES ARE DEFINED AS FOLLOWS:

$$h_{eff} = \frac{h_1 A_1 + h_2 A_2}{A_1 + A_2}$$

$$T_{eff} = \frac{h_1 A_1 T_1 + h_2 A_2 T_2}{h_1 A_1 + h_2 A_2}$$

WHERE,

$h_1 A_1 T_1$ ARE CONDITIONS ON ONE SIDE OF ELEMENTS

AND

$h_2 A_2 T_2$ ARE CONDITIONS ON OTHER SIDE OF ELEMENTS

THESE VALUES ARE LISTED IN TABLE 1

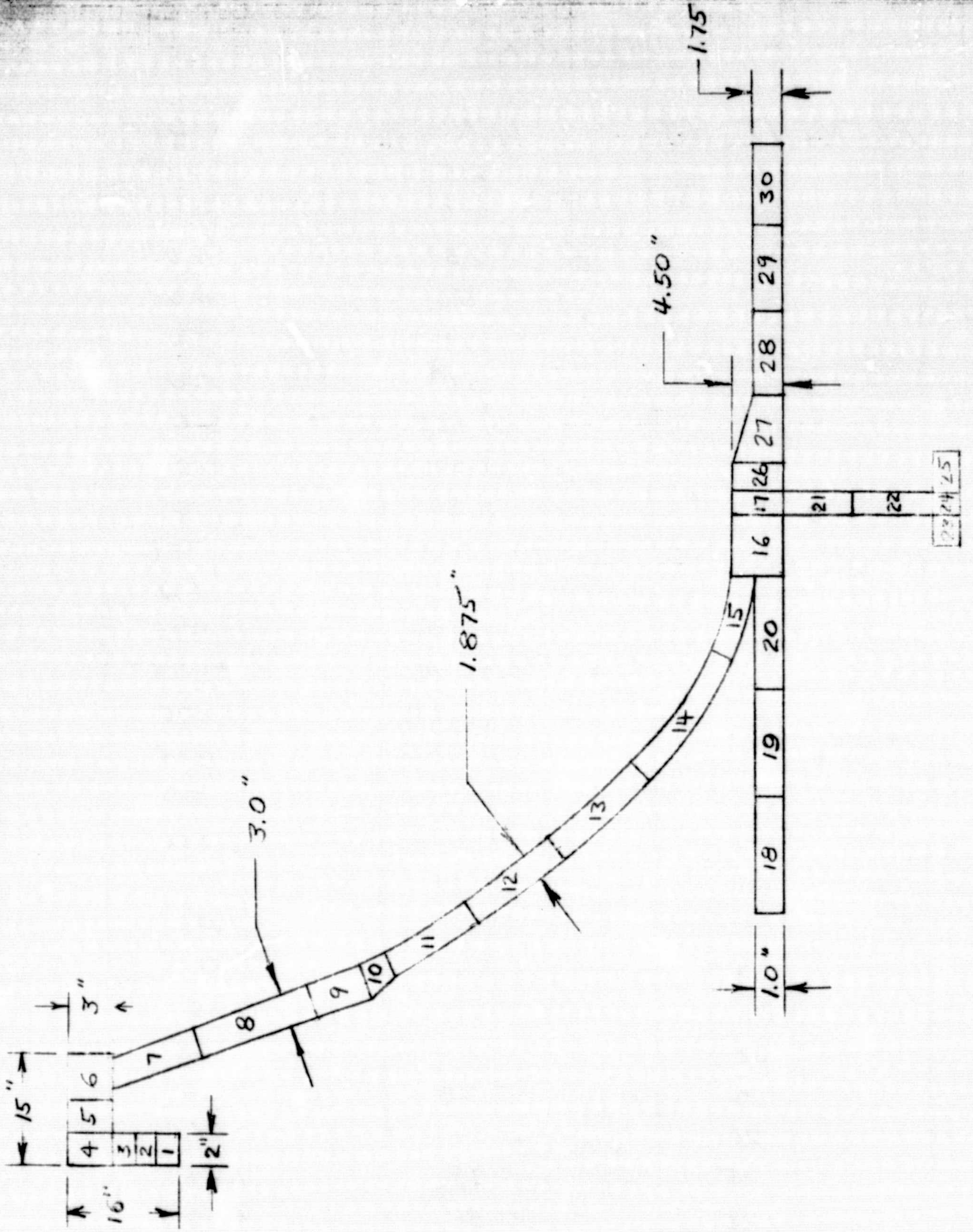

1.75"
4.50"
1.875"
3.0"
3"
15"
2"
16"
1.0"
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22
23
24
25
26
27
28
29
30

FIGURE - 1

DIMESIONS

ELEMENT NO.	LENGTH	WIDTH
1	6.5"	4.0"
2	4.0	4.0"
3	2.5	4.0"
4	5.0	4.0"
5	5.0	5.0
6	5.0	5.0
7	11.657	3.0
8	20.001	3.0
9	5.309	3.0
10	2.721	2.438
11	16.985	1.875
12	11.284	1.875
13	13.019	1.875
14	14.228	1.875
15	4.908	1.875
16	14.380	1.50
17	1.240	1.50
18	24.00	1.0
19	18.0	1.0
20	18.0	1.0
21	1.24	7.25
22	1.24	12.08
23	5.38	1.24
24	1.24	1.24
25	5.38	1.24
26	2.88	4.50
27	8.50	3.125
28	12.00	1.75
29	21.00	1.75
[illegible]	[illegible]	[illegible]

BY________ DATE________ SUBJECT________ SHEET NO. 9 OF________
CHKD. BY________ DATE________ JOB NO.________

TABLE 1

(FLOW BOUNDARY CONDITIONS)

ELEMENT NO.	HEAT TRANSFER COEFFICIENT (BTU/IN²-SEC·°F)	GAS TEMPERATURE (°R)
1	1.066×10^{-5}	160
2	7.566×10^{-6}	
3	7.566×10^{-6}	
4	1.10×10^{-5}	
5	5.401×10^{-6}	
6	8.524×10^{-6}	
7	4.726×10^{-7}	
8		
9		
10		
11		
12		
13		
14		
15	4.726×10^{-7}	160
16	1.711×10^{-6}	506
17	4.726×10^{-7}	160
18	1.698×10^{-6}	505
19	1.698×10^{-6}	505
20	1.698×10^{-6}	505
21	2.894×10^{-6}	560
22		
23		
24		
25	2.894×10^{-6}	560
26	1.711×10^{-6}	506
27	1.706×10^{-6}	506
28	1.7×10^{-6}	505
29	1.7×10^{-6}	505
30	1.7×10^{-6}	505

RESULTS

THE TEMPERATURE DISTRIBUTION WAS CALCULATED FOR THE MODEL SHOWN IN FIGURE 1. THE UPDATED MODEL, SHOWN IN FIGURE 2, SHOWS THE FINAL DIMENSIONS OF THE BULKHEAD. A COMPARSION WILL BE SHOWN IN THE TRANSIENT ANALYSIS THAT THIS CHANGE IN DIMESIONS DOES NOT EFFECT THE TEMPERATURES OF THE BULKHEAD SINCE THE HEAT TRANSFER COEFFICIENT IS LARGE "ENOUGH" TO GIVE UNIFORM TEMPERATURE IN THE FLANGE AREA.

THE TEMPERATURE DISTRIBUTION OF THE BULKHEAD IS SHOWN IN FIGURE 3. THIS AGREES WITHIN 3° OF FLUIDYNE'S CALCULATED RESULTS SHOWN IN FIGURE 4.

THE STRESSES FOR THIS CASE WILL NOT BE CALCULATED SINCE THE TEMPERATURE GRADIENTS ARE NOT AS SEVERE AS IN TRANSIENT CASE SHOWN ON FIGURE 11. THE STRESSES ARE SHOWN ON FIGURES 12, 13, AND 14.

THE UPDATED CONFIGURATION OF THE TUNING FOLK IS SHOWN IN FIGURE 5. THE TEMPERATURE WILL BE SIMILAR TO THAT SHOWN IN FIGURE 5 SINCE THE TEMPERATURE GRADIENTS IN THIS AREA ARE SMALL COMPARED TO THE INNER FLANGE. THE STRESSES IN THIS AREA ARE ALSO SMALL AS SHOWN IN FIGURES 12, 13, AND 14.

UPDATE OF
THERMAL MODEL OF BULKHEAD

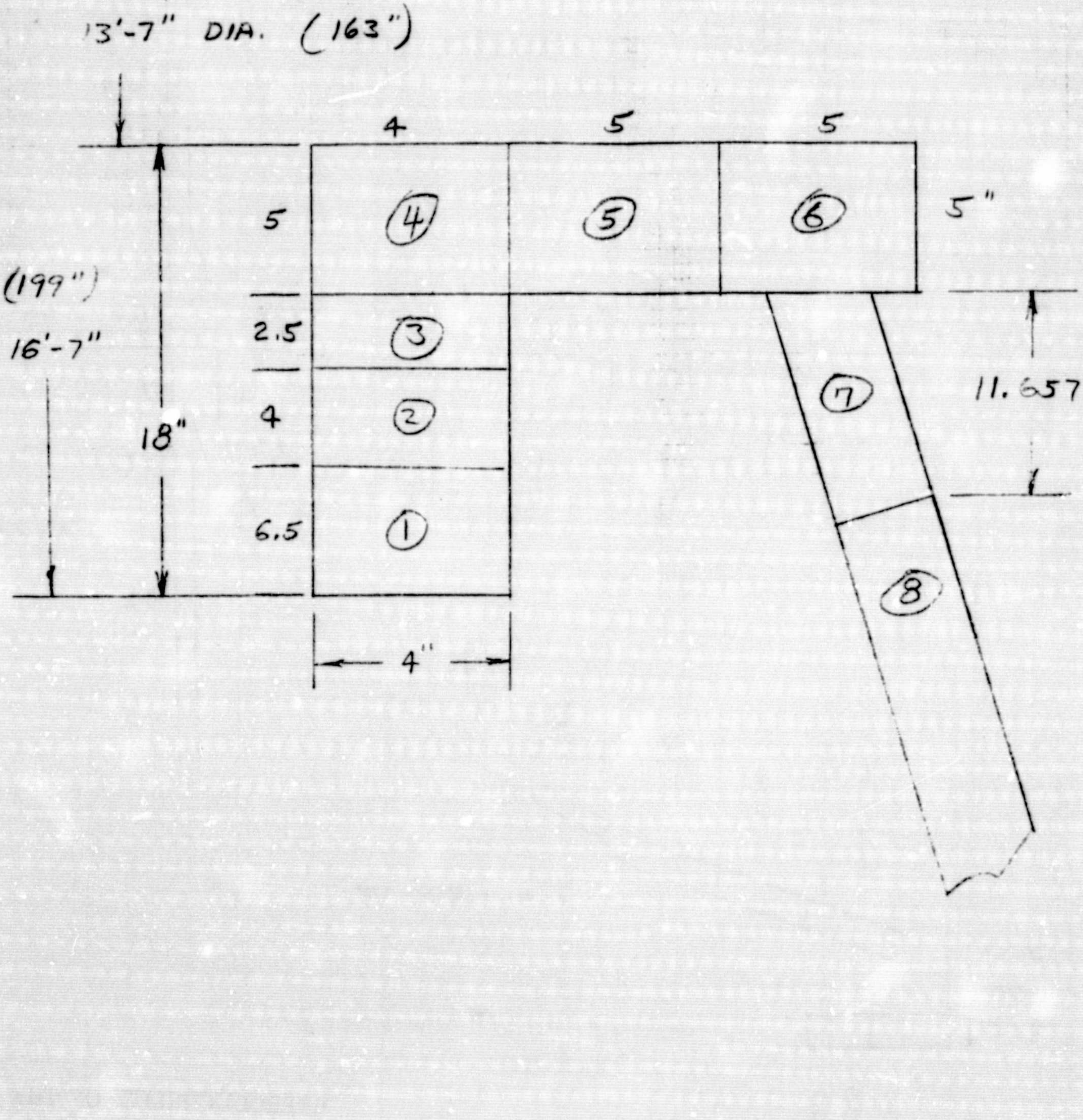


FIGURE 2

BY ________ DATE ________ SUBJECT ________ SHEET NO. 12 OF ____

CHKD. BY ________ DATE ________ JOB NO. ________

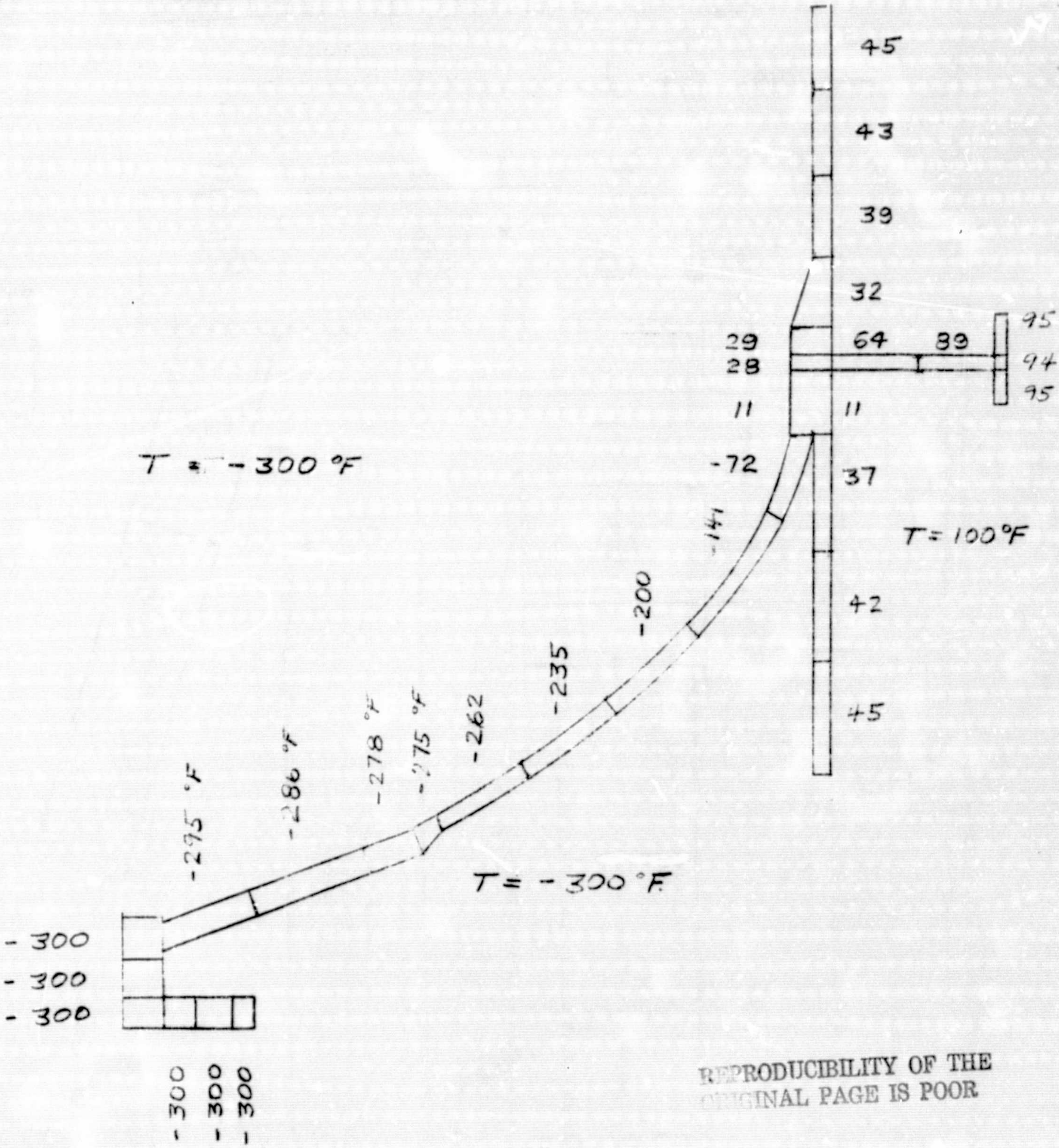


FIGURE 3

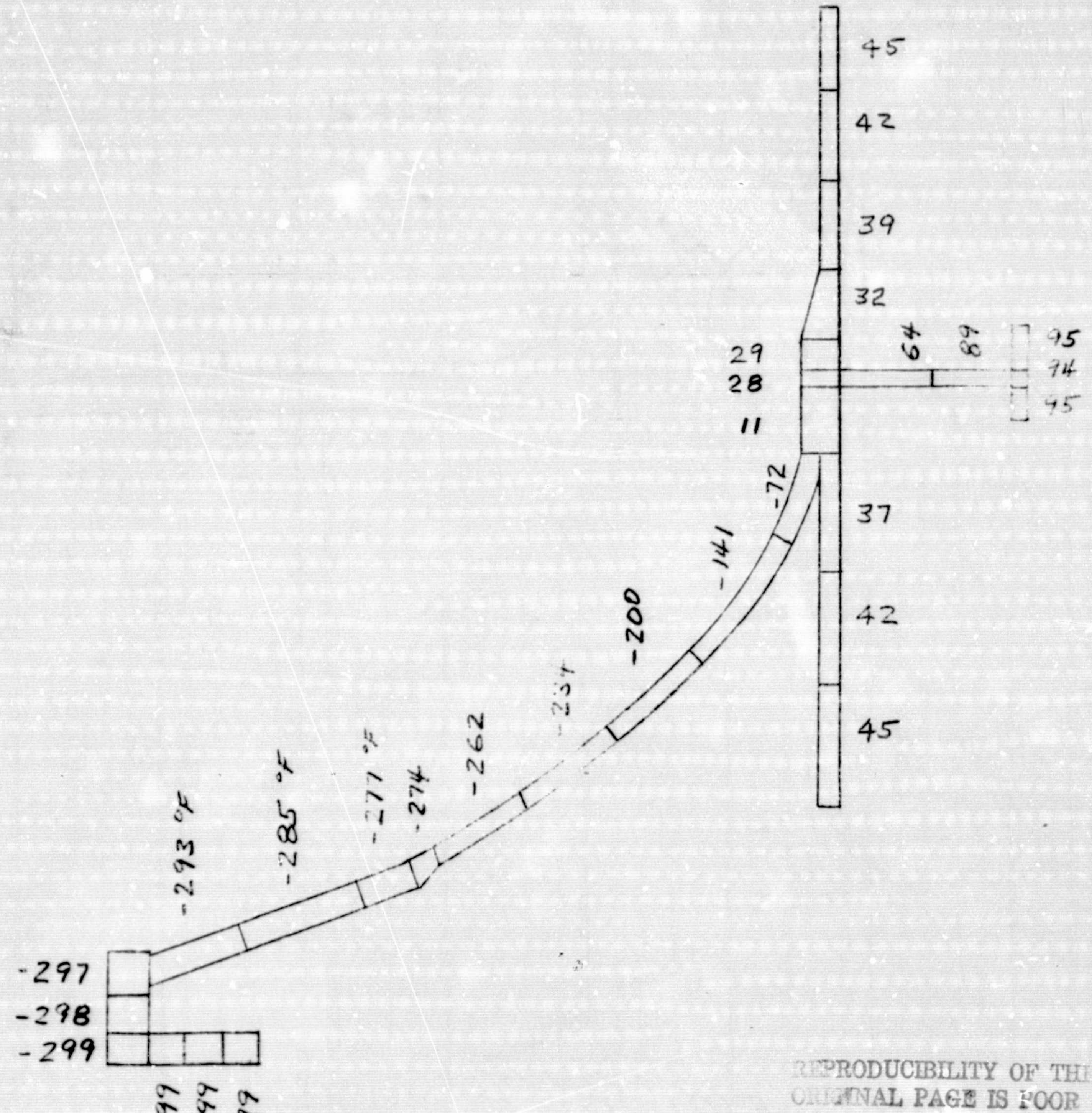


FIGURE 4

(FLUIDYNE RESULTS)

BY________ DATE________ SUBJECT________________________ SHEET NO. 14 OF______
CHKD. BY______ DATE________ JOB NO.________________

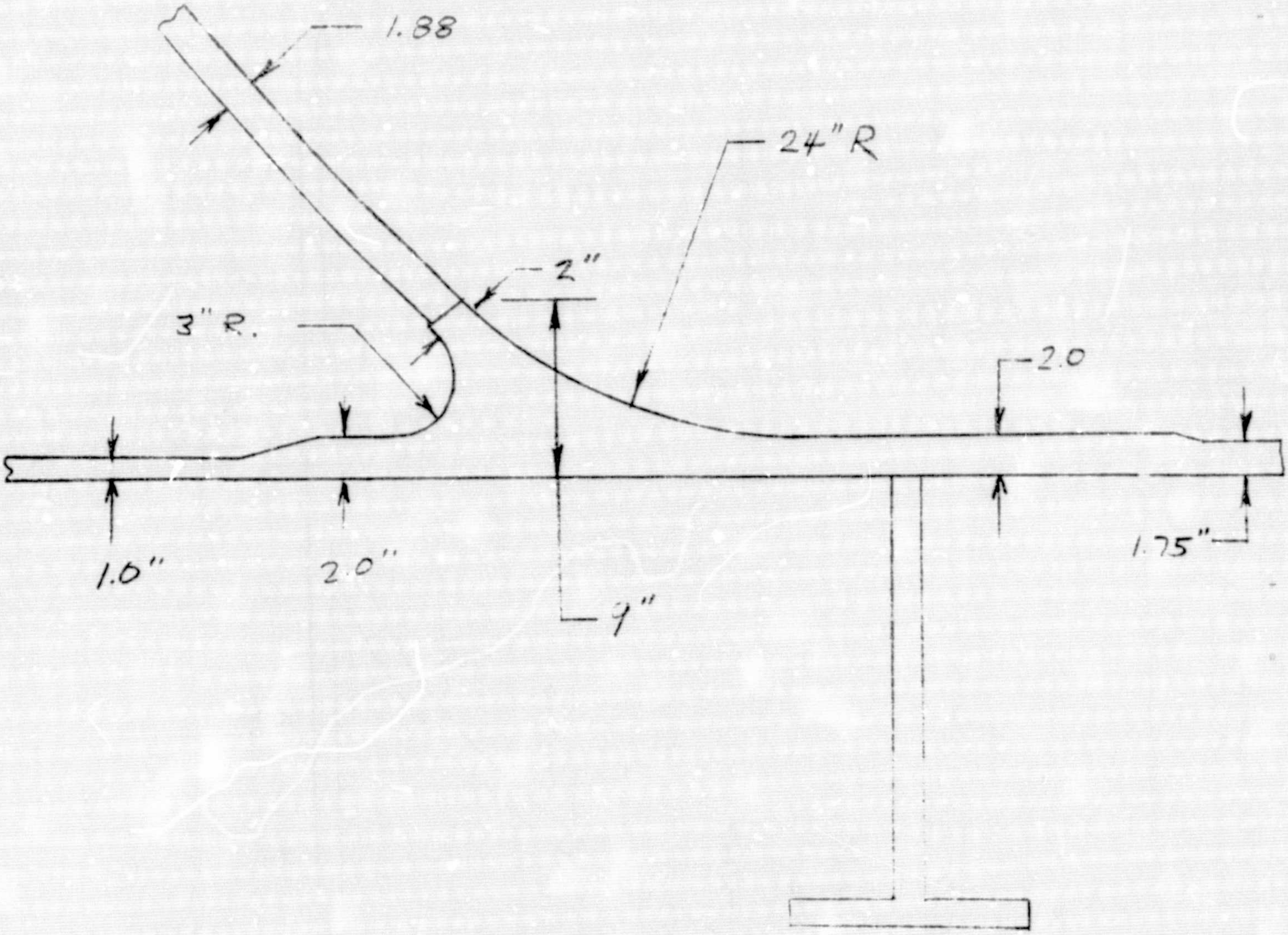
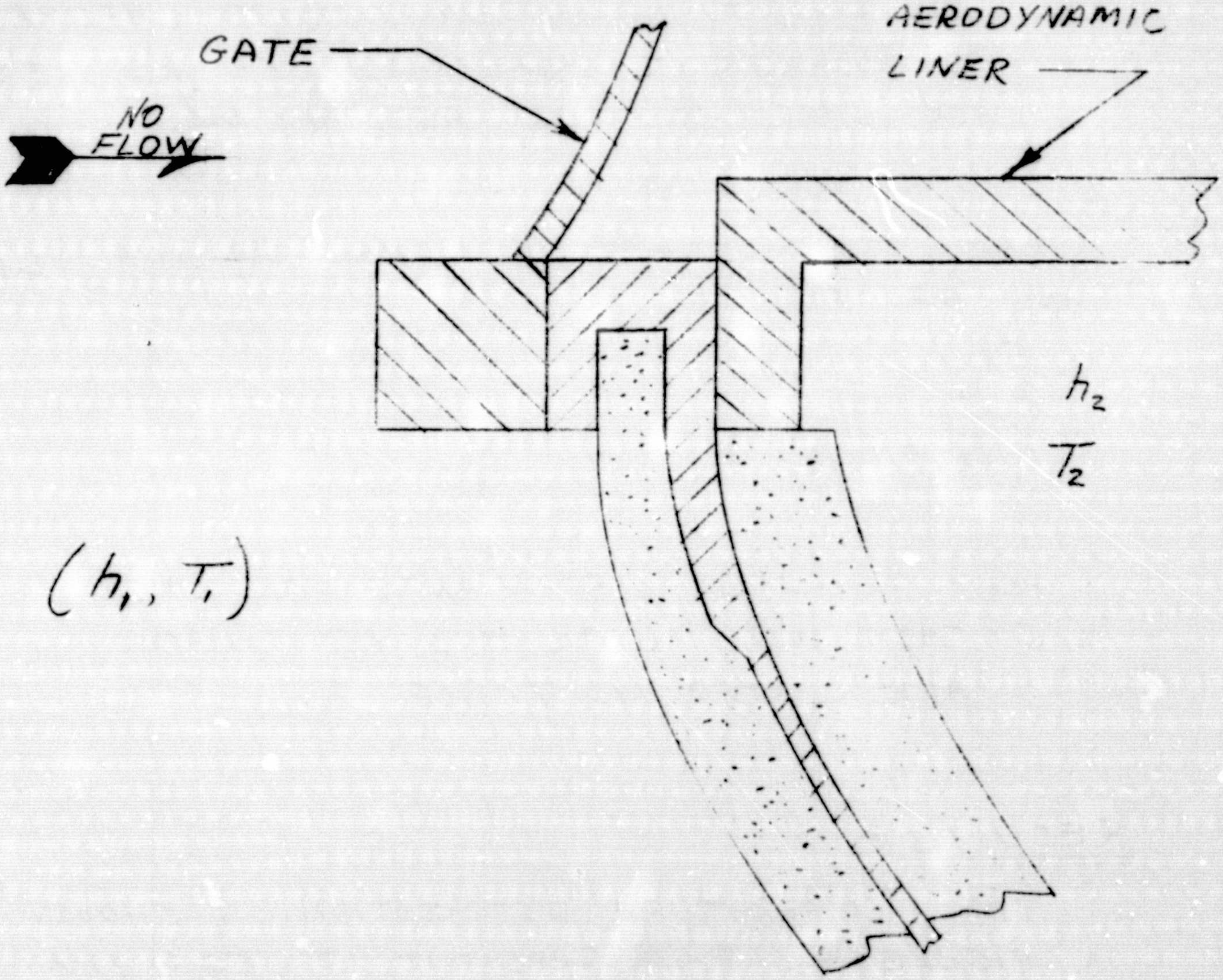


FIGURE 5

(FINAL DIMENSIONS OF TUNING FOLK)

B- GATE VALVE CLOSED - NO FLOW

THIS STEADY STATE CASE EXISTS WHEN THE GATE VALVE IS CLOSED WITH THE FOLLOWING BOUNDARY CONDITIONS:



ASSUMPTIONS:

1- ASSUME h_1 & h_2 ARE LARGE, THEREFORE THE SURFACES EXPOSED TO THE GAS ARE ASSUMED TO BE THE SAME AS THE GAS TEMPERATURE.

2- ASSUME TEMPERATURE OF GATE IS -100°F (THIS ASSUMPTION IS CHECKED IN TRANSIENT ANALYSIS) SEE RESULTS FOR CHECK ON THIS ASSUMPTION.

BOUNDARY CONDITIONS:

THE STEADY STATE BOUNDARY CONDITIONS ARE AS FOLLOWS:

$$\begin{cases} T_1 = -300\,°F \\ T_2 = 100\,°F \end{cases}$$

HEAT TRANSFER COEFFICIENTS FOR LINER IN CONTACT WITH GATE AND AERODYNAMIC LINER ARE LISTED IN TABLE 2.

RESULTS:

THE TEMPERATURE DISTRIBUTION IS SHOWN IN FIGURE 6. THIS GRADIENT IS LESS THAN THE FLOW DISTRIBUTION SHOWN IN FIGURE 3. THE TEMPERATURE GRADIENT THRU THE WALL THICKNESS IN NEGLIGBLE. THEREFORE THE THICKNESS THERMAL STRESS WILL BE SMALL. THE LOCAL GRADIENT AT THE GATE VALVE

IS LESS THAN GRADIENTS SHOWN LATER FOR THE TRANSIENT HEATING OF THE PLEMUM.

THE ASSUMED GATE TEMPERATURE OF -100°F WAS INCORRECT. THE FINAL GATE TEMPERATURE CALCULATED FROM THE THERMAL ANALYSIS IS -260°F. THE TRANSIENT ANALYSIS WILL GIVE A MORE SEVERE TEMPERATURE AS SHOWN IN NEXT SECTION.

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TABLE 2

(NONFLOW THERMAL BOUNDARY CONDITIONS)

ELEMENT NO.	HEAT TRANSFER COEFFICIENT (Btu/IN^2-sec-°F)	GAS TEMPERATURE (°R)
1	1.0×10^{-3}	360
2		360
3		360
4		439
5		560
6	1.0×10^{-3}	560
7	4.723×10^{-7}	360
8		
9		
10		
11		
12		
13		
14		
15	4.723×10^{-7}	360
16	1.711×10^{-6}	560
17	4.723×10^{-7}	560
18	1.698×10^{-6}	505
19		505
20	1.698×10^{-6}	505
21	2.894×10^{-6}	560
22		
23		
24		
25	2.394×10^{-6}	
26	1.683×10^{-6}	
27	1.711×10^{-6}	
28	1.70×10^{-6}	
29	1.70×10^{-6}	
30	1.70×10^{-6}	560

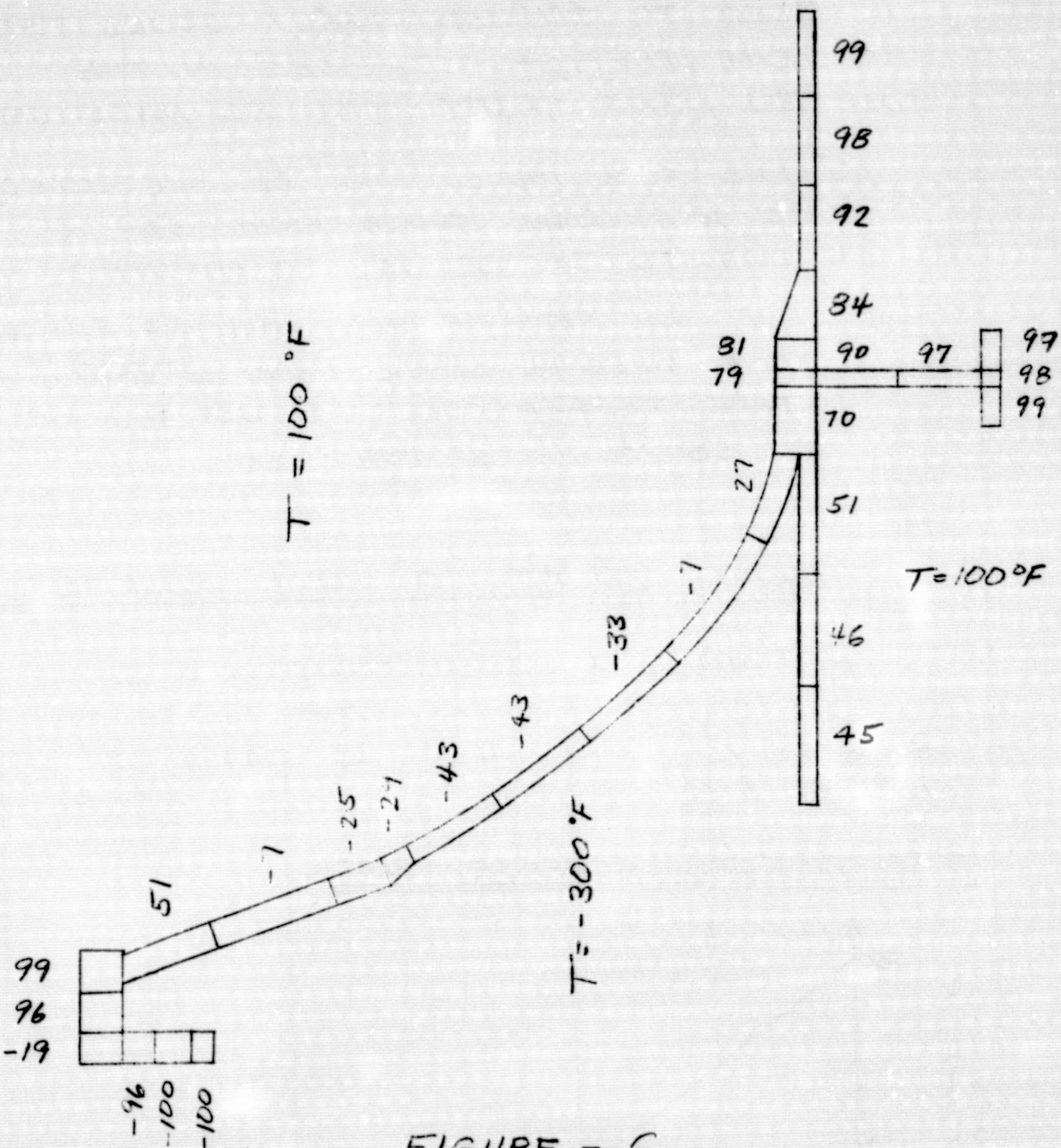

99
98
92
84
81
79
90
97
97
98
99
70
27
51
T=100°F
T = 100 °F
-7
46
-33
45
-43
-43
-25
-21
T= -300°F
51
-7
99
96
-19
-96
-100
-100

FIGURE - 6

II. TRANSIENT ANALYSIS OF BULKHEAD

IN ORDER TO CONSERVATIVELY BOUND THE TRANSIENT THERMAL STRESSES IN THE BULKHEAD, TWO CASES WILL BE INVESTIGATED

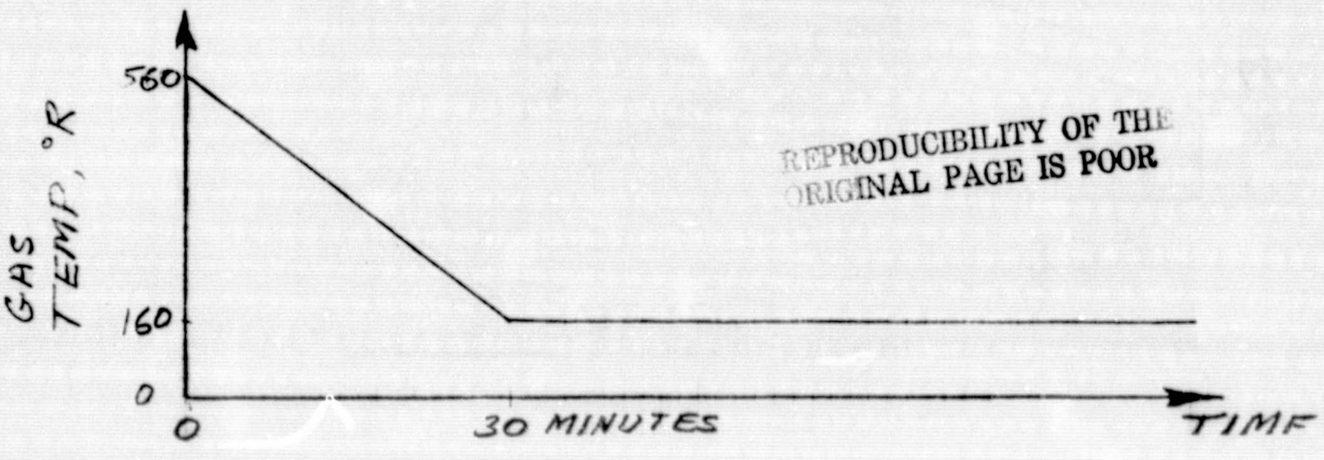
A- THE FLOW MODEL WILL BE SUBJECTED TO A THERMAL SHOCK FROM 560 °R DOWN TO 160 °R IN 30 MINUTES.

B- THE NON FLOW MODEL WILL BE SUBJECTED TO A THERMAL SHOCK FROM STEADY STATE TEMPERATURES (FIGURE 3) UP TO 560 °R IN 30 MINUTES.

A- THERMAL SHOCK TO COOL BULKHEAD

THE MODEL + ASSUMPTIONS ARE SAME AS FLOW CASE IN STEADY STATE CASE. THE GEOMETRY IS SAME ALSO AS SHOWN IN FIGURE 1.

TEMPERATURE DECREASE PLOT



RESULTS

THE TEMPERATURE DISTRIBUTION CALCULATED IN THE TRANSIENT HEAT TRANSFER PROGRAM IS SHOWN IN FIGURE 7. THIS WORST CASE TO BRING PLEMUM DOWN TO 160°R OCURRED AFTER 30 MINUTES FROM START OF COOL DOWN. THE MAXIMUM TEMPERATURE DIFFERENCE IS 346 °F BETWEEN ELEMENTS 6 AND 7. THIS LARGE GRADIENT TEMPERATURE DISTRIBUTION AT TIME EQUAL TO 30 MINUTES WAS INPUT INTO THE "SPAR" PROGRAM TO CALCULATE THE RESULTANT STRESSES. THESE STRESSES ARE SHOWN IN FIGURE 8.

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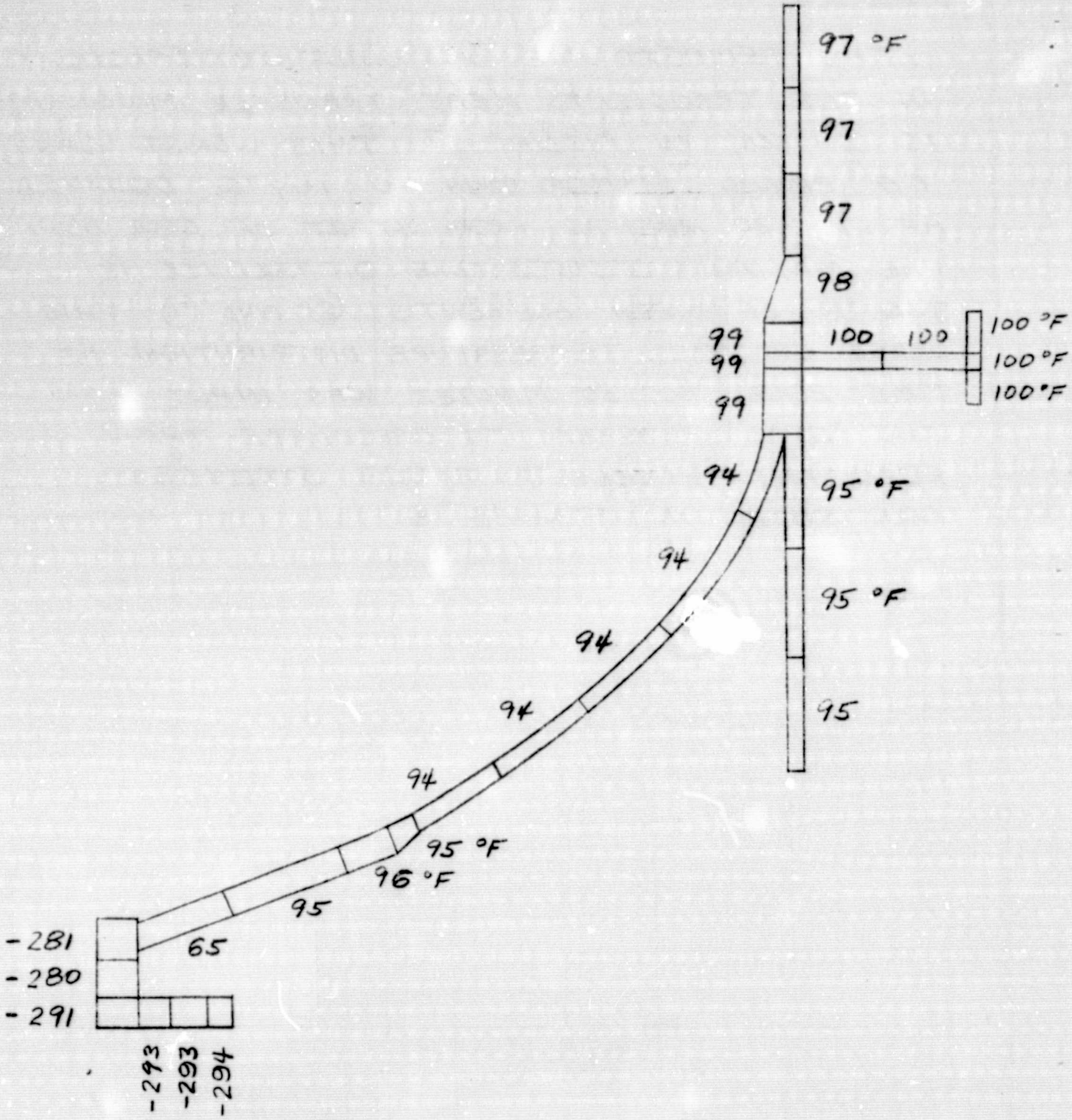

FIGURE - 7

BY ______ DATE ______ SUBJECT ______ SHEET NO. ______ OF ______
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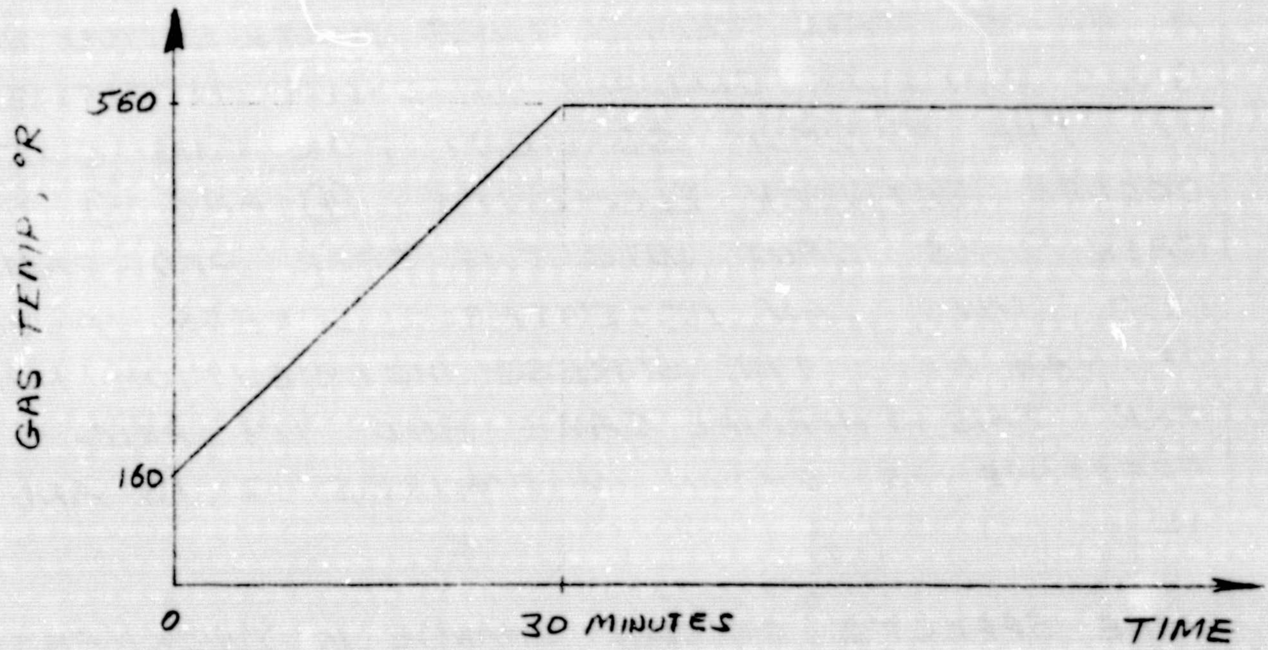
B- THERMAL SHOCK TO HEAT BULKHEAD

THE MODEL + ASSUMPTIONS ARE SAME AS NONFLOW CASE IN STEADY STATE CASE. THE GEOMETRY IS SAME AS SHOWN IN FIG. 1. THE INITIAL TEMPERATURE OF BULKHEAD BEFORE HEAT UP IS SAME AS STEADY STATE DISTRIBUTION WITH FLOW. THIS WAS SHOWN IN FIGURE 3. THE ASSUMPTION IS MADE THAT THE HEAT UP STARTS AS SOON AS THE GATES ARE CLOSED.

TEMPERATURE INCREASE PLOT



RESULTS

THE TEMPERATURE DISTRIBUTION FOR THE 30 MINUTE HEAT UP TIME IS SHOWN IN FIGURE 9. THIS MAXIMUM TEMPERATURE OCURRS AT 30 MINUTES AFTER THE START OF HEAT UP. THE TEMPERATURE DIFFERENCE IS LARGEST BETWEEN ELEMENTS 6 AND 7. (ΔT = 323 °F). THIS TEMPERATURE DISTRIBUTION WAS INPUT INTO THE SPAR PROGRAM TO CALCULATE MAXIMUM STRESSES (THERMAL AND PRESSURE). THE STRESSES ARE SHOWN IN FIGURE 10.

THE MAX. STRESS IS -51 KSI WHICH IS BELOW THE ALLOWABE OF 52.5 KSI. NOW, RERUN THE TEMPERATURE PROGRAM FOR A HEAT UP TIME OF 4 HOURS. THIS TEMPERATURE DISTRIBUTION WHICH GIVES MAXIMUM GRADIENT IS SHOWN IN FIGURE 11. THE MAXIMUM GRADIENT FOR THIS CASE OCCURS BETWEEN ELEMENTS 4 AND 5. THIS CASE WAS INPUT INTO THE SPAR PROGRAM ALSO GIVING AN ACCEPTABLE STRESS VALUE OF -44 KSI. THE STRESS DISTRIBUTION FOR THE THIS THERMAL CASE AND 119 PSIG PRESSURE IS SHOWN IN FIGURES 12, 13 AND 14.

THE EFFECTS OF THE CHANGE IN THICKNESSES OF THE BUCKHEAD WERE CHECKED BY RE-RUNNING THE TRANSIENT HEAT TRANSFER PROGRAM. THESE THICKNESSES ARE SHOWN IN FIGURE 2. THE TEMPERATURES SHOWN IN FIGURE 15 ARE ALMOST EQUAL TO THOSE SHOWN IN FIGURE 11.

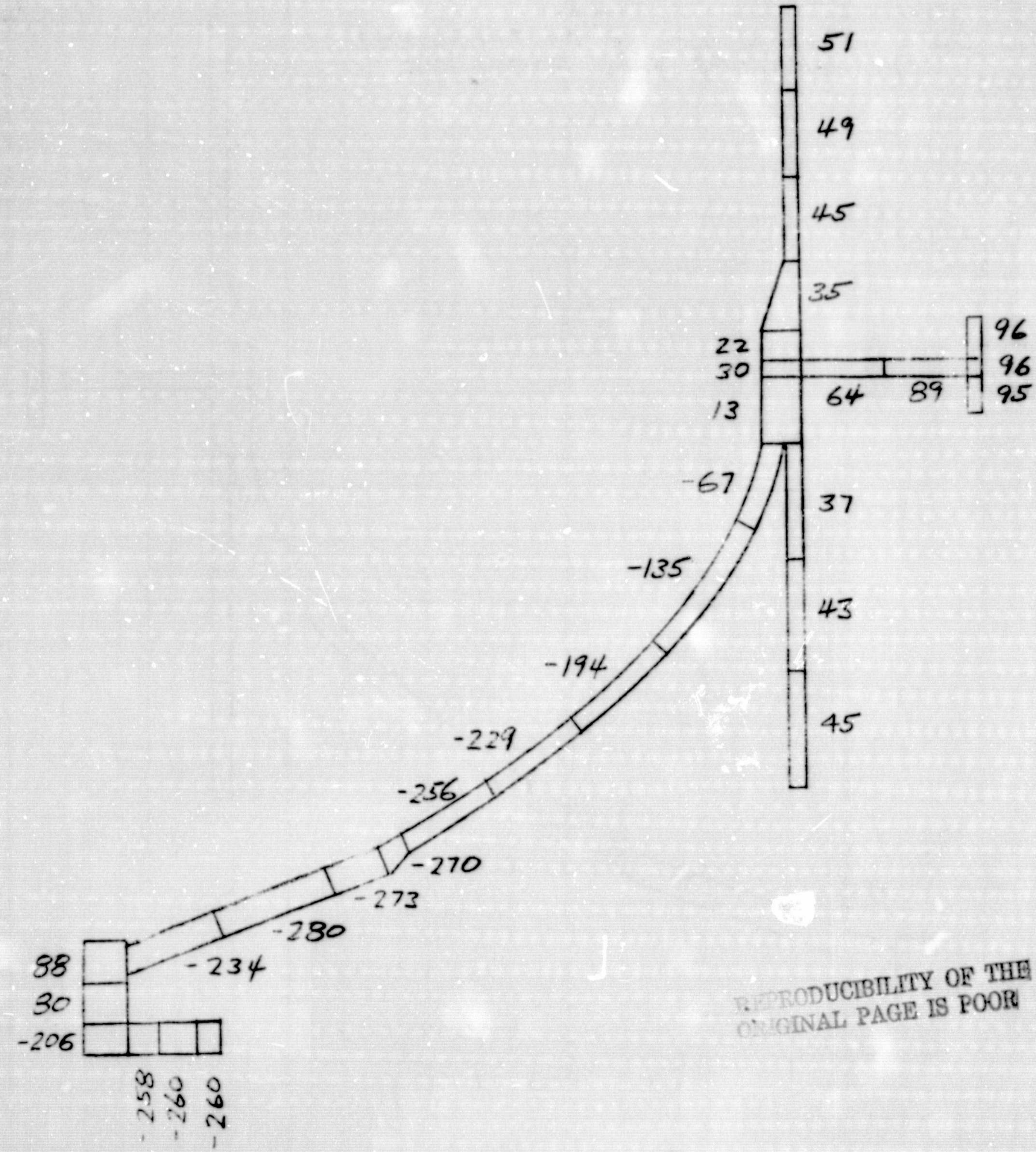


FIGURE - 9

(HEAT UP TIME OF 30 MINUTES)

STRESS INTENSITY

GATE VALVE CLOSED WITH TRANSIENT
TEMPERATURE AND PRESSURE

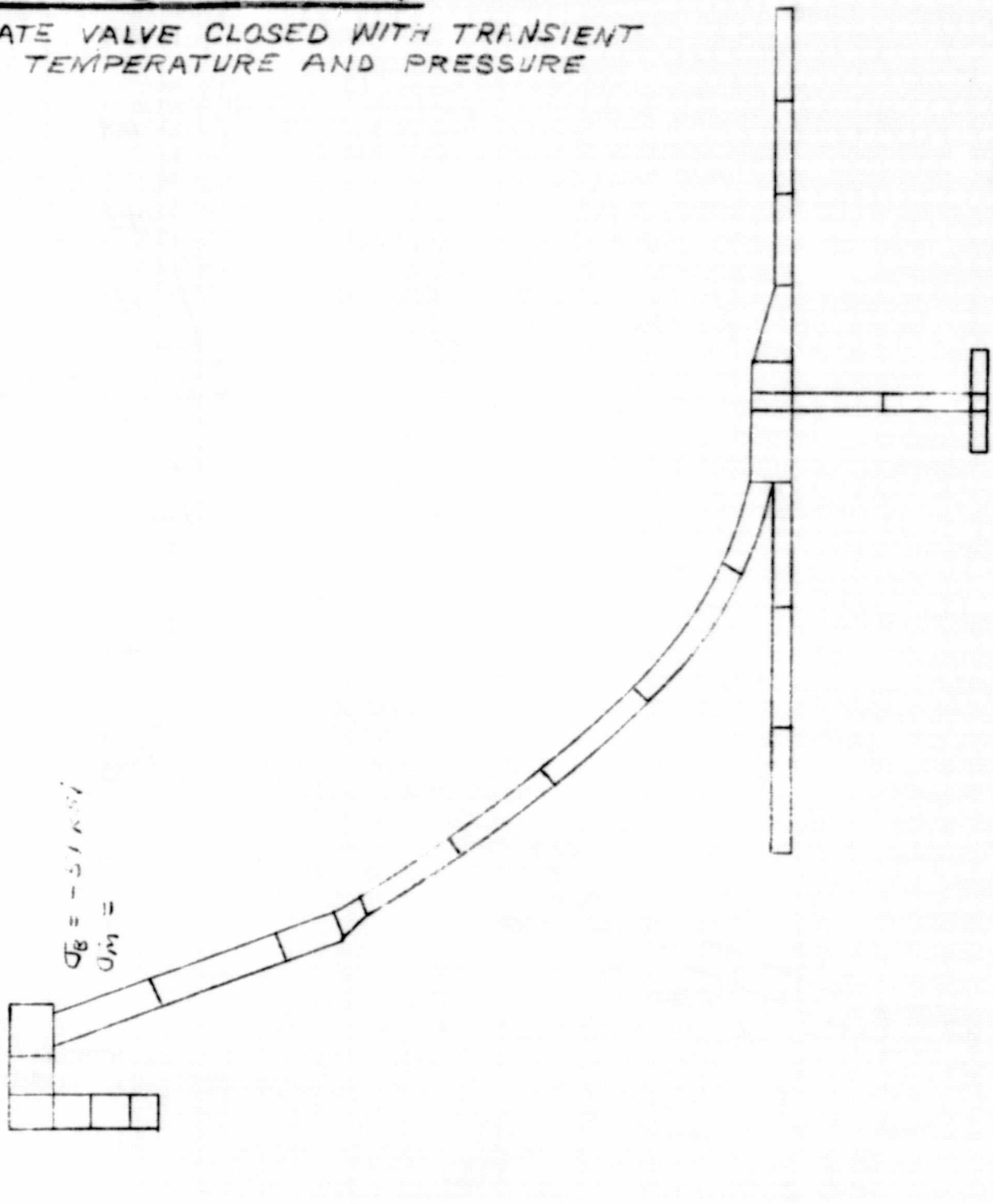


FIGURE - 10

BY DATE SUBJECT SHEET NO.
CHK'D BY DATE JOB NO.

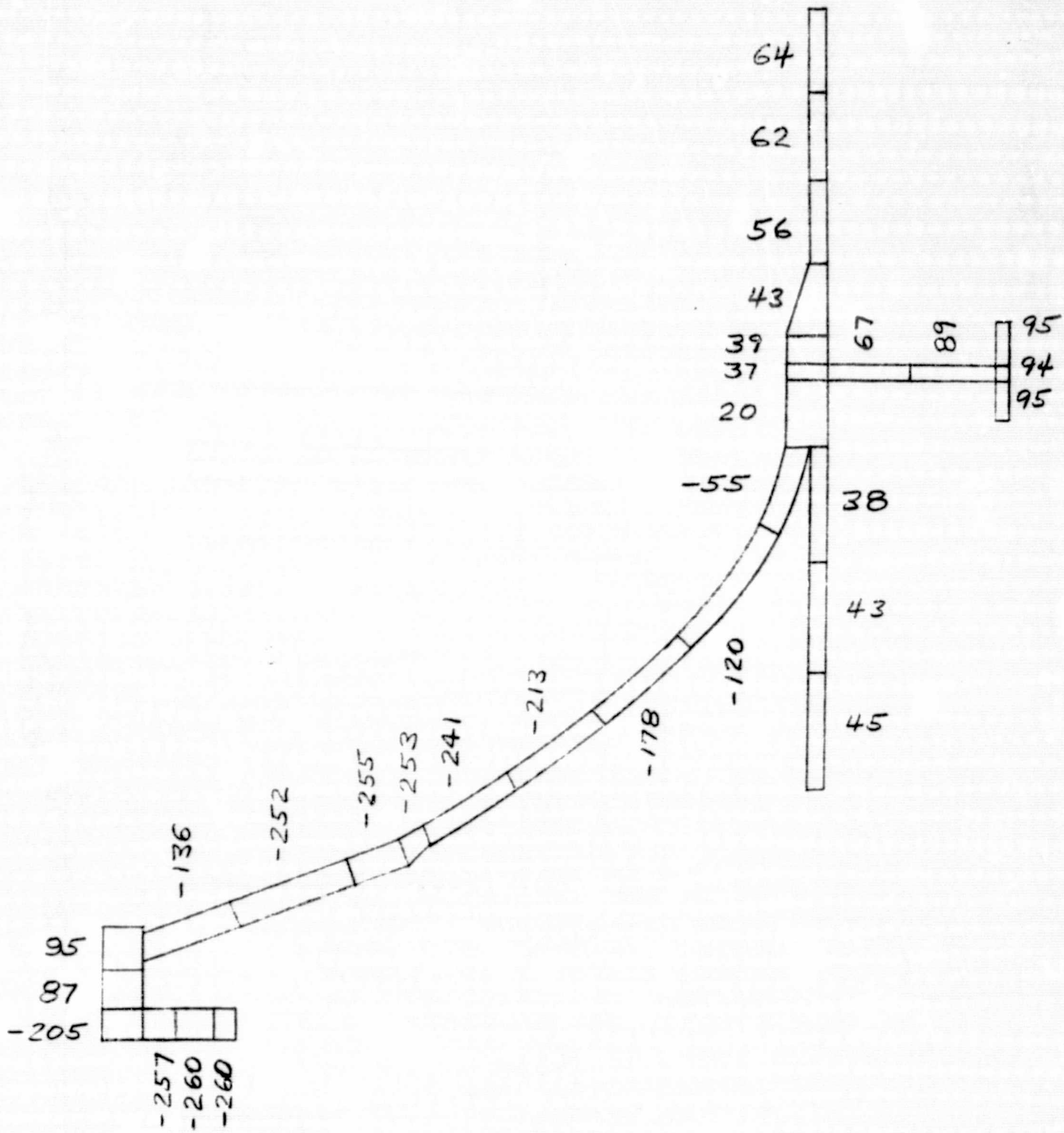


FIGURE - 11

(HEAT UP TIME OF 4 HOURS)

FIGURE 12 C

Tran. Temp. Valve Closed

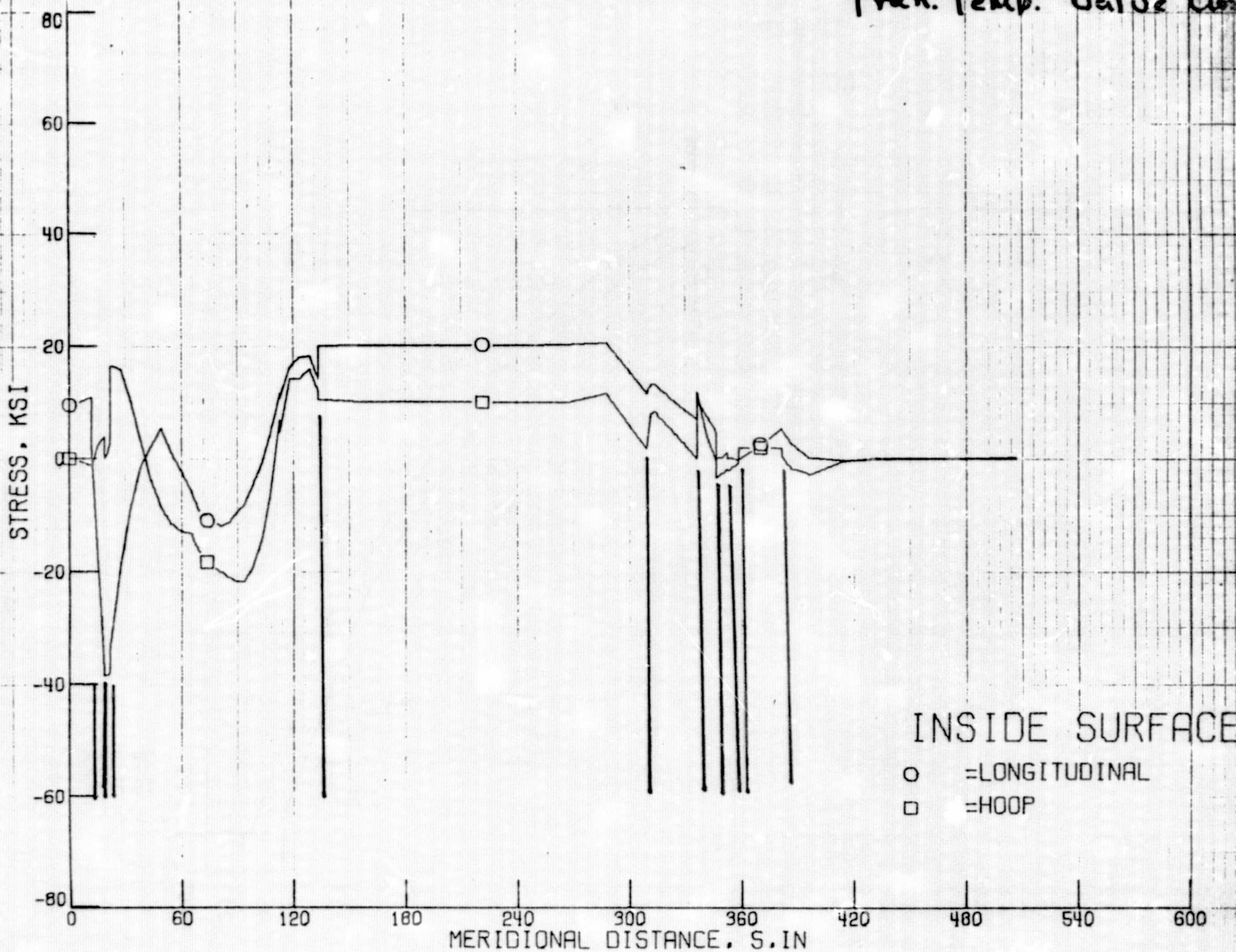
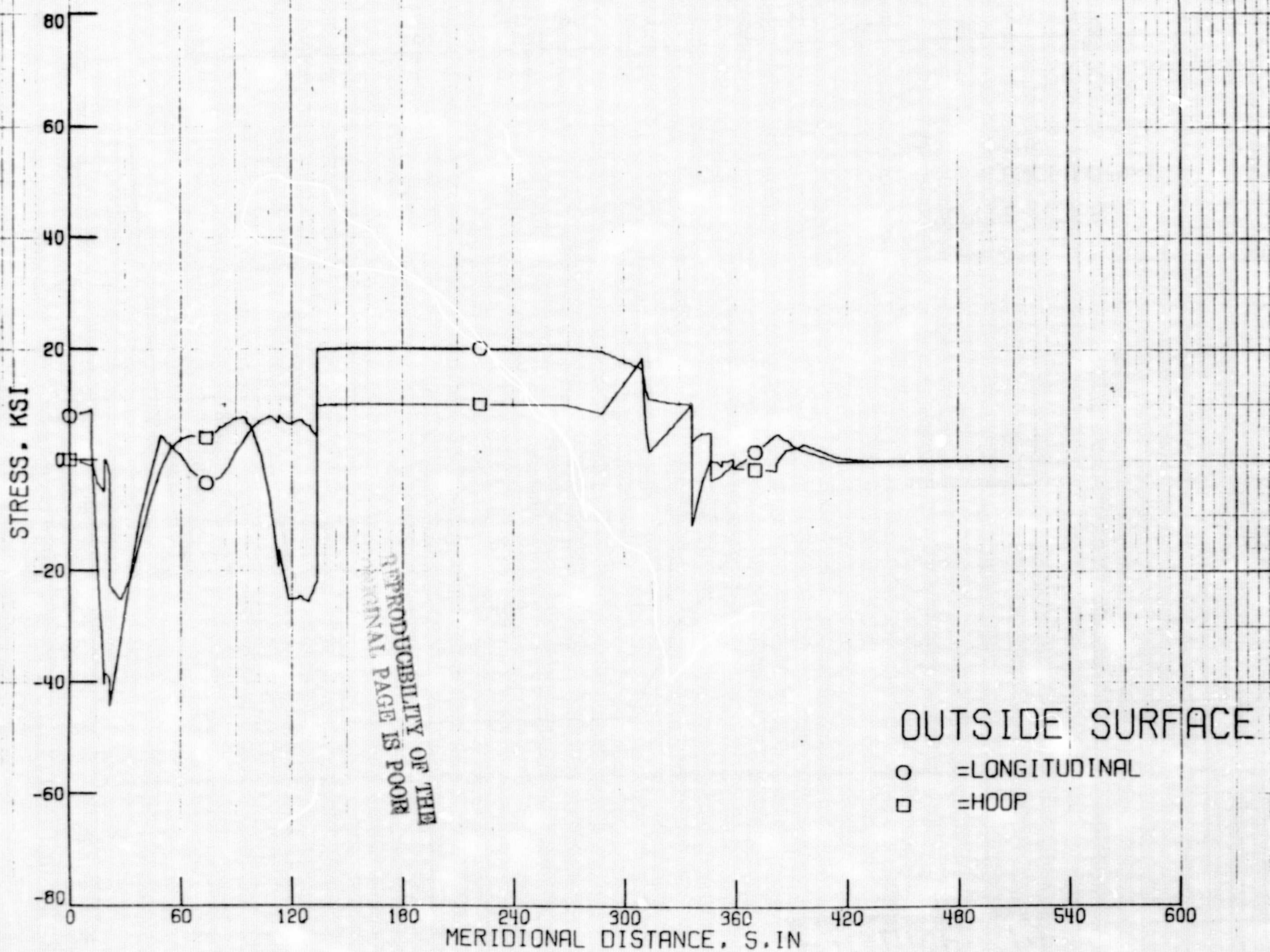
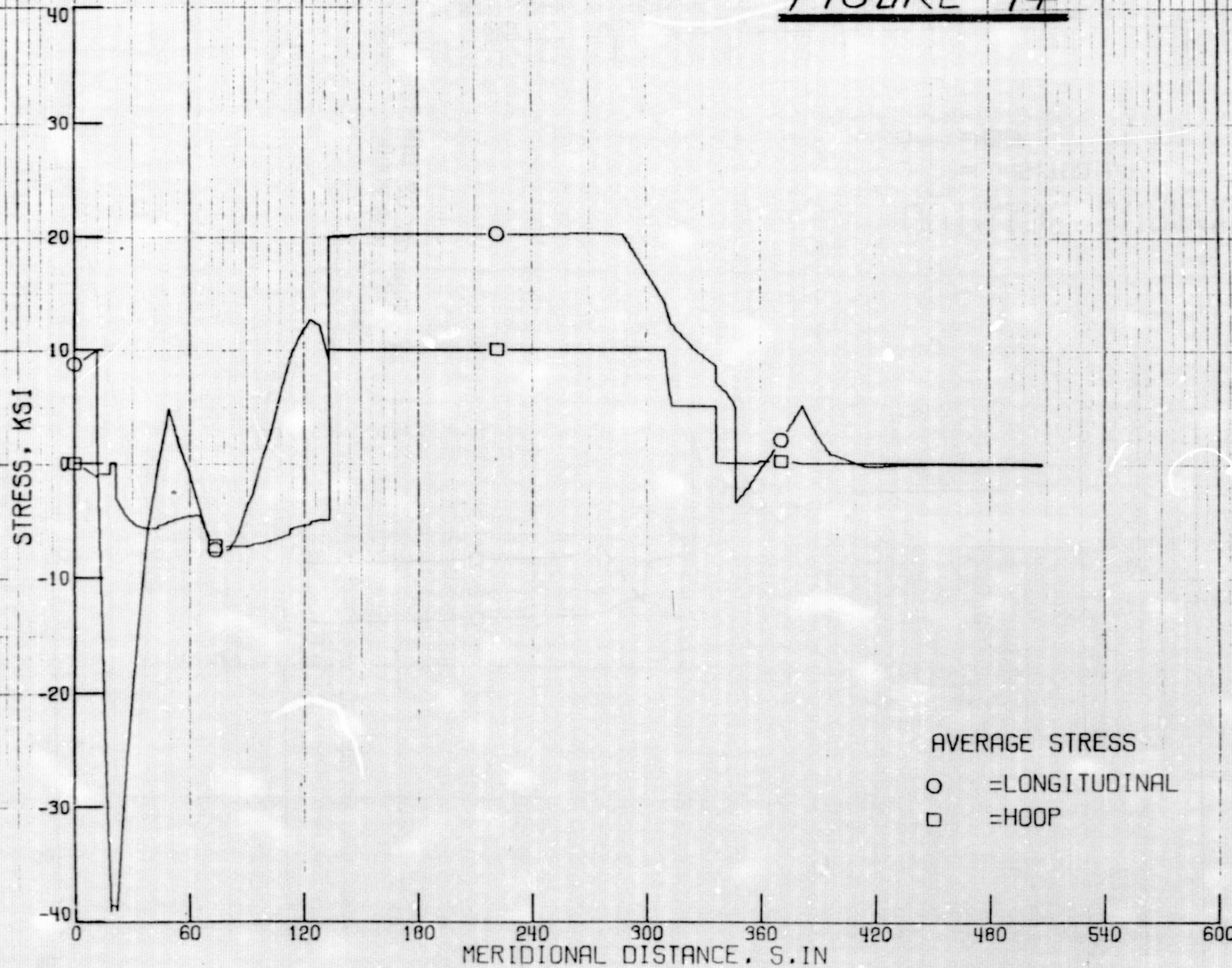


FIGURE 13



80
60
40
20
0
-20
-40
-60
-80
STRESS, KSI
0
60
120
180
240
300
360
420
480
540
600
MERIDIONAL DISTANCE, S.IN
OUTSIDE SURFACE
O =LONGITUDINAL
□ =HOOP

FIGURE 14



40
30
20
10
0
-10
-20
-30
-40
STRESS, KSI
0
60
120
180
240
300
360
420
480
540
600
MERIDIONAL DISTANCE, S.IN
AVERAGE STRESS
○ =LONGITUDINAL
□ =HOOP

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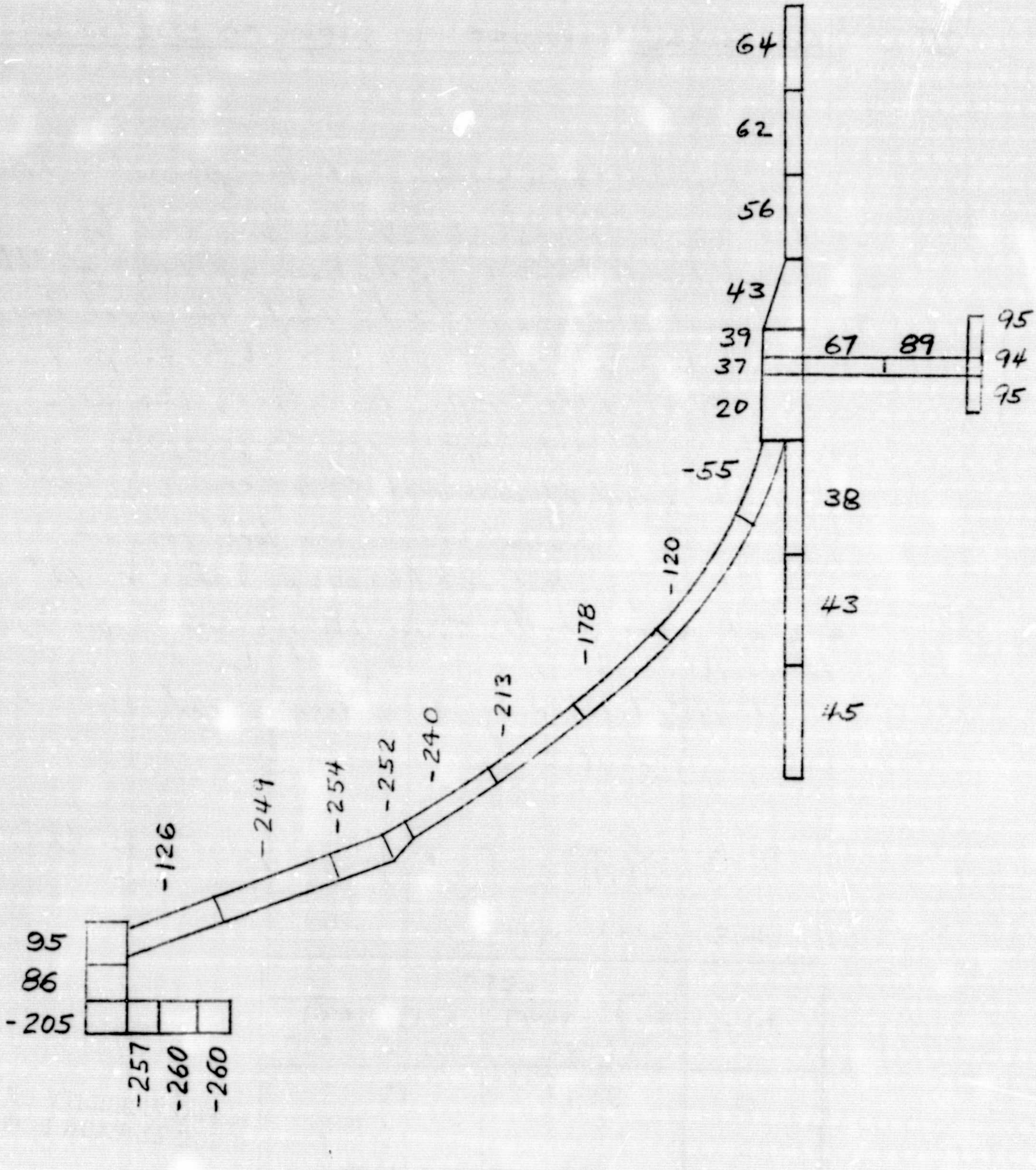

FIGURE 15

III – ACCIDENTAL EXPOSURE OF SHELL TO LN_2 OR GN_2

A thermal stress analysis of the pressure shell between corner rings S6 & S7 has been conducted for the local loss of insulation or LN_2 puddle. The thermal analysis indicates that the local loss of insulation will drive the bare shell temp. to within 3° of LN_2 temp.; therefore, the LN_2 puddle could not impose any more severe gradient than this, and it was not considered any further. The resulting thermal stresses for local loss of insulation peaked out (60,000 psi) for a 12° arc of bare shell. These stresses were superimposed to existing stresses at typical structural ring and elliptical ring to determine reduction in fatigue life for these areas.

N_a = number of operating cycles with bare shell

L = Life years

Na	LIFE	
	TYP STRUCT RING	ELLIPTICAL RING WELD
0	31	15
1	31	15
10	29	15
50	25	14
100	21	12

Therefore the local loss of insulation or LN2 puddle would effect the fatigue life of sections of the tunnel differently. The important point is that this type of accident needs to be detected before a large number of cycles are accumulated.

Detail supporting calculations follow.

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ACCIDENTAL EXPOSURE OF SHELL TO LN2 or GN2

Two types of accidents can occur which would expose the shell to LN2 or GN2

1. Loss of insulation
   this would expose shell to gaseous N_2
2. LN2 Puddle

I LOSS OF INSULATION

The worse place to loose insulation is the region where insulation is the flow liner and the flow has a high velocity. This occurs in the short leg between corner rings 56 & 57.

A FILM COEF

Gas Film Coef.

The flow area changes in the short leg.
The entrance has a 16' DIA and at midway an annulus is formed by the upstream nacelle. Therefore, will calculate an average coeff.

Annulus: $D_o = 20$ ft $D_i = 10$ ft

$$A = \frac{\pi}{4}(20^2 - 10^2) = 235.62\ ft$$

$$\text{Average } A = \frac{1}{2}\left[235.62 + \frac{\pi 16^2}{4}\right] = 218\ ft^2$$

$$RE = \frac{\dot{m} D}{\mu A}$$

Assume @ Test Section M=1
P_0 = 1 ATM (gives coldest temp)
$T_0 = -320°F$

Test section area - $(2.5m \times 3.2808\ ft/m)^2 = 67.27\ ft^2$

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$$\frac{A}{A^*} = \frac{218}{67.27} = 3.25 \Rightarrow M = .18 \quad P/P_0 = .9776 \quad \frac{T}{T_0} = .994$$

$$M=1 \quad \frac{P}{P_0} = .528 \quad \frac{T}{T_0} = .8333$$

$$P_{TS} = 1\,atm(.528) = .528\ ATM$$

$$T_{TS} = (140).8333 = 116.66\,°R$$

Short leg Areas:-

$$P_{SL} = .9776\ ATM \quad T_{SL} = 139\,°R$$

$$\mu = 2.16 \times 10^{-7} \frac{slugs}{ft\text{-}sec\sqrt{°R}} \left[\frac{139^{3/2}}{139+184}\right] \frac{32.17\ lbm}{slug} = 3.524 \times 10^{-6}$$

$$\mu = 3.524 \times 10^{-6} \frac{lbm}{ft\text{-}sec}$$

$$\dot{m} = 45{,}000 \frac{lbm}{sec}$$

For Circle $\frac{\pi D^2}{4} = A$ or $D = \sqrt{\frac{4A}{\pi}}$

16.66 ft

$$RE = \frac{\left(45{,}000 \frac{lbm}{sec}\right)\sqrt{4\,\frac{218\ ft^2}{\pi}}}{3.524 \times 10^{-6} \frac{lbm}{sec\text{-}ft}\ 218\ ft^2} = 9.76 \times 10^{8}$$ ← Turbulent pipe flow

using pipe flow equations based on bulk fluid temp: for $\Delta T \leq 100°F$

$$N_{NU} = .023\,(N_{RE})^{.8}(N_{PR})^{.4}$$

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$P_r = .739$ $K = .01045 \frac{Btu}{hr\,ft\,°F}$ ← estimates

$$h_g = \frac{(.023)(9.76\times10^8)^{.8}(.739)^{.4}\left(.01045 \frac{Btu}{hr\,ft\,°F}\right)}{16.66\,ft} = 198.7 \frac{Btu}{ft^2\text{-}hr\,°F}$$

Apply short length correction factor to mid point of short leg:-

$$h_g = 198.7 \left(\frac{16.66}{4.2}\right)^{1/18} = 202$$

$\therefore h_g = 200 \frac{Btu}{ft^2\text{-}hr\,°F}$

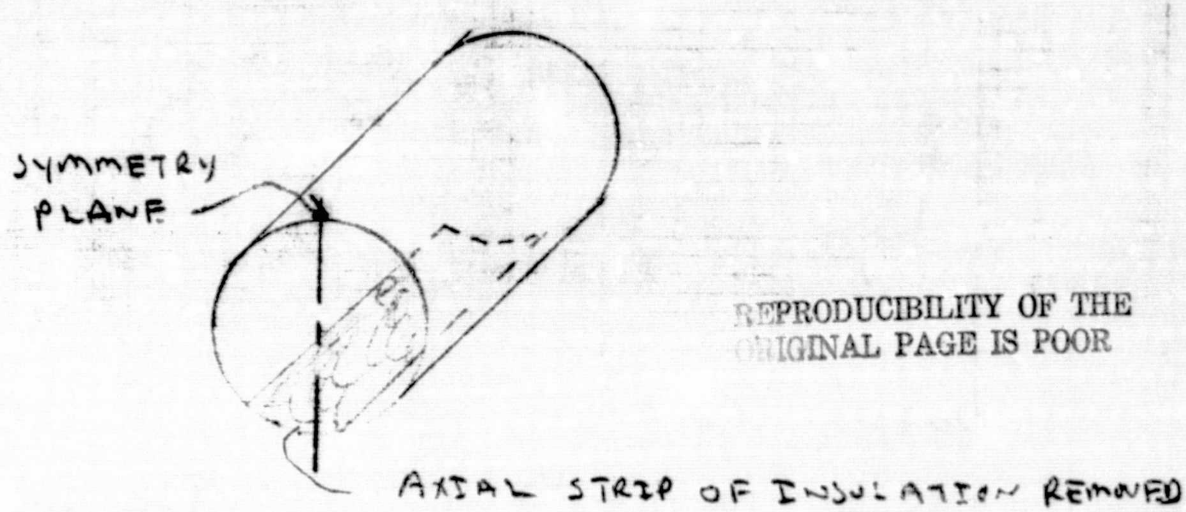
Outside Coef:-

$h_o = .18 (\Delta T)^{1/3} \frac{Btu}{ft^2\,hr\,°F}$ $T_o = 100°F$

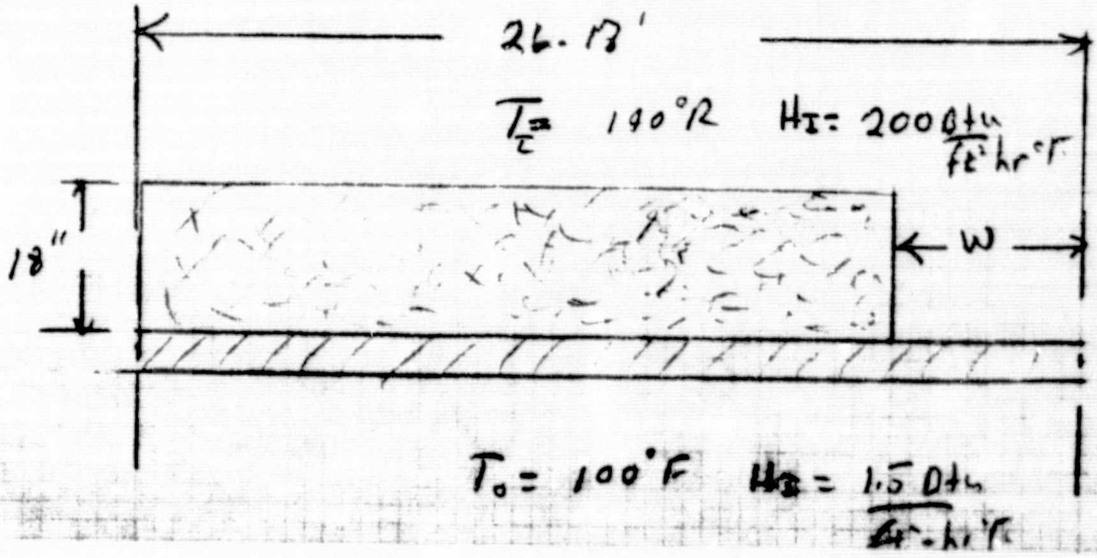
use $h_o = 1.5 \frac{Btu}{ft^2\,hr\,°F}$ as 1st estimate

B. THERMAL MODEL

The short leg will be used as the typical section to model. It will be assumed that a section of insulation will be removed for the entire length of leg.



Symmetry will be taken advantage of, and the shell will be unwrapped to form a linear model.



C. COMPUTER INPUT

The width of the insulation loss will be varied.

The insulation will be treated as an effective film coef. for modeling purposes and the shell will be divided into 30 blocks (maximum that program will handle

LEN = 26.17/30 = .87 ft or 10.47 in

WID = .67 in

VOL = 17.01 for 1" thk

Effective Film Coef inside:-

For a one dimensional heat balance on insulated plate:

$$Q = \frac{T_O - T_S}{\frac{1}{h_I A_I} + \frac{t_I}{K_I A_c}}$$

For effective film coef:-

$$Q = h_{eff} A_{eff} (T_S - T_I)$$

$$h_{eff} A_{eff} = \frac{1}{\frac{1}{h_I A_I} + \frac{t_I}{K_I A_c}}$$

Neglecting curvature of shell:-

$$A_I = A_c = A$$

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$$h_{eff} = \frac{1}{\frac{1}{h_I} + \frac{t_I}{k_I} + \cdot}$$

For insulated shell:-

$$h_{eff} = \frac{1}{\frac{1}{\frac{1.389\ Btu}{in^2\ hr\ ^\circ F}} + \frac{18\ in \times 144\ in^2/ft^2}{\frac{1.47\ Btu\text{-}in}{ft^2\ hr\ ^\circ F}}} = \frac{5.669 \times 10^{-4}\ Btu}{in^2\ hr\ ^\circ F}$$

For uninsulated shell:-

$$h_{eff} = h_g = \frac{1.389\ Btu}{in^2\ hr\ ^\circ F}$$

from previous work on bulkheads; the effective coef. & Temps for blocks with different convective boundary conditions:-

$$h_{eff} = \frac{h_i A_i + h_o A_o}{A_i + A_o}$$

For $A_i = A_o = A$

$$h_{eff} = \frac{(h_i + h_o) A}{2A} = \frac{h_i + h_o}{2}$$

$$T_{eff} = \frac{h_i A_i T_i + h_o A_o T_o}{h_i A_i + h_o A_o}$$

$$T_{eff} = \frac{(h_i T_i + h_o T_o)}{h_i + h_o}$$

BY________ DATE________ SUBJECT________ SHEET NO.____ OF____

CHKD. BY________ DATE________ JOB NO.________

For the insulated blocks:-

$$h_{eff} = \left[\frac{5.669\times10^{-4} + \frac{1.5}{144}}{2}\right] = .00549 \ \frac{Btu}{in^2\,hr\,°F}$$

$$T_{eff} = \left[\frac{(5.669\times10^{-4})(140) + (.01042)560}{2(.00549)}\right] = 539°$$

For the uninsulated blocks:-

$$h_{eff} = \frac{1.389 + .01042}{2} = .7 \ \frac{Btu}{in^2\,hr\,°F}$$

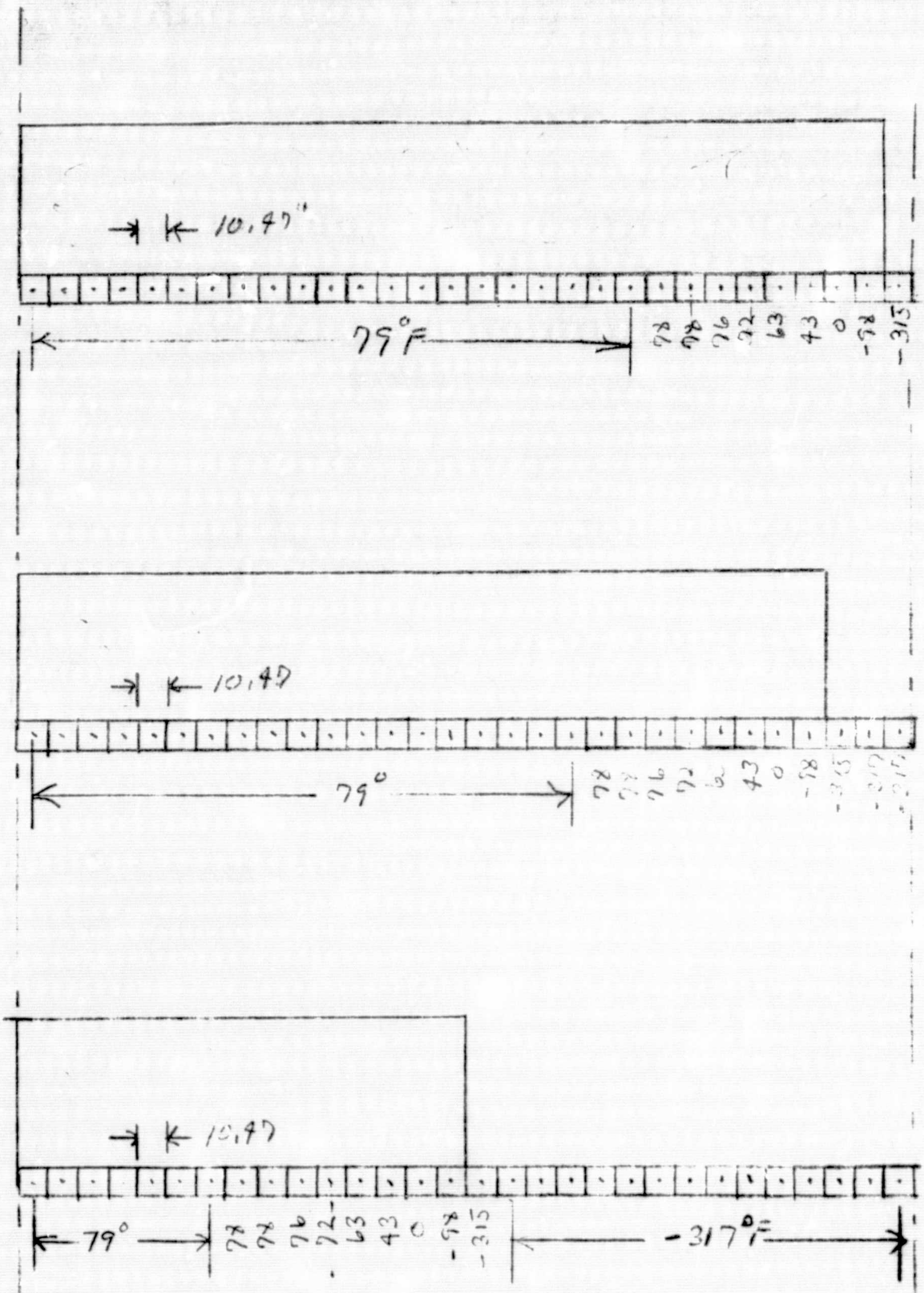
$$T_{eff} = \frac{(1.389)(140) + (.01042)(560)}{2(.7)} = 143\ °R$$

$$ACOND = (1)(.67) = .67\ in^2$$

$$CROAREA = 2A = (10.47)(1) = 10.47\ in^2$$

BY .... DATE .... SUBJECT .... SHEET NO. ...... OF ......

CHKD. BY ...... DATE .... JOB NO. ....



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II LN_2 PUDDLING

Liquid Nitrogen puddling is a more complex problem than insulation loss. However, the resulting temperature distribution can be no worse than insulation loss because the bare shell temp. with no insulation is within 3° of the LN_2 temp. Therefore the results from the "insulation loss" case will bracket both of these accident problems.

III THERMAL STRESS IN SHELL

A CLOSED FORM SOLUTION

A closed form solution will be used to estimate the thermal stresses in the short leg region of the shell. This region will be modeled as a right circular cyl. with constant temp. thru the thk and circumferential temp. variation. This type of temp. dist. will cause thermal stresses in both the hoop and axial directions. However, due to the flexibility of a thin shell in the hoop direction (as compared to axial direction) the hoop stresses will be small compared to those in the axial direction. Therefore, only those stresses in the axial direction will be considered.

From ref 1, Axial stress (σ_x):-

$$\sigma_x = -\alpha E T(\phi) + \frac{E}{2\pi}\int_0^{2\pi} \alpha T(\phi)\, d\phi + \frac{E \sin\phi}{\pi}\int_0^{2\pi} \alpha T(\phi) \sin\phi\, d\phi$$

$$+ \frac{E\cos\phi}{\pi}\int_0^{2\pi} \alpha T(\phi) \cos\phi\, d\phi$$

The above equation is for NO constraint. The second term is dropped for axial constraint and the last two are dropped for bending constraint. These equations were programmed for 3 types of boundary conditions:

1. Completely constrained
2. [illegible]
3. NO Restraint

PHI = N*H/R

```
      PROGRAM LN2STRS(INPUT, OUTPUT, TAPE
      DIMENSION [illegible], TEMP(10) SUM(10), WK(10)
      COMMON R, H
      EXTERNAL FXL,
      READ *, E ALPHA, PHI, NTEMP
      READ *, TEMP

 10
      READ*, A, B, H, N

      CALL SIMP(A, B, FX, H, N, SUM, WK, IERR)
       IF (IERR .NE. 0.) GO TO 500
      DO 10 I = 5, NTEMP, 5
 10   PHI = I * H/R
      SIGX1 = - ALPHA*E * TEMP(I) + E/PI * (SUM(1)/2.

       + SIN(PHI)* SUM(2) + COS(PHI) SUM(3)
       THETA = 180. * PHI /PI
      PRINT *, THETA, SIGX
 10   CONTINUE
```

A = 0
B =
H = 15.9
N = 3
R = 99.7
E = 29X10^6
ALPHA = 6.5X10^-6
PI = 3.14159
NTEMP = 61

628.2

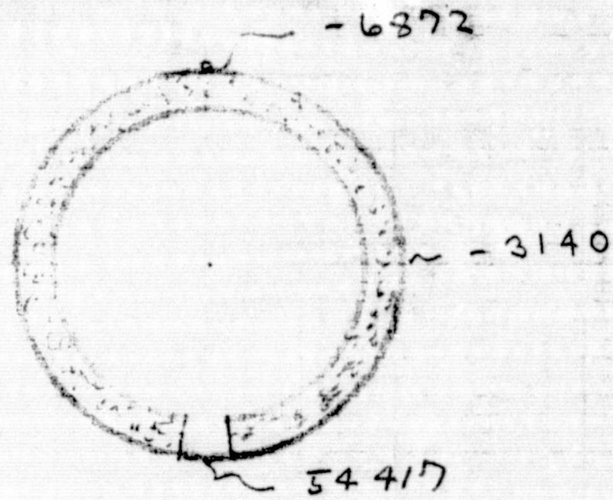
R = 99.96

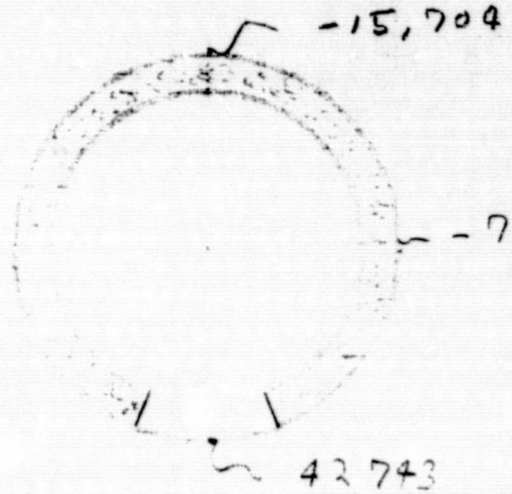
STRESSES

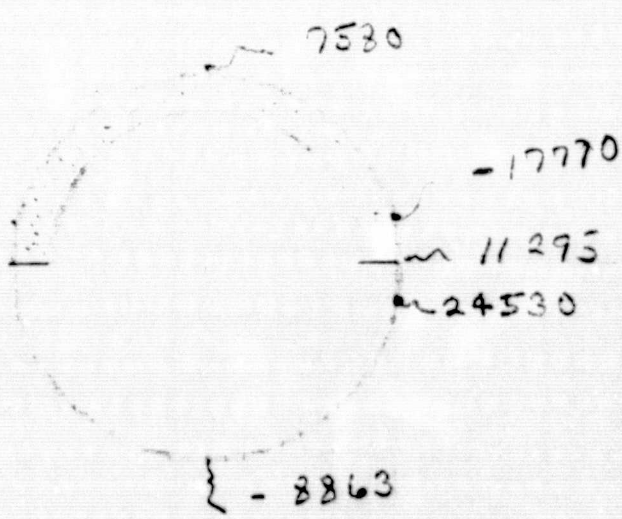
```
                         LI#
 PROGRAM LM2STRS(INPUT,OUTPUT)
 DIMENSION SUM(10),WK(10)
 COMMON R,H,TEMP(61)
 EXTERNAL FX
 READ*,A,B,H,N,E,ALPHA,PI,NTEMP,R
 READ*,TEMP
 CALL SIMP(A,B,FX,H,N,SUM,WK,IERR)
 PRINT*,SUM(1),SUM(2),SUM(3)
 IF(IERR.EQ.0) 20,30
3 PRINT*,IERR
3 DO 10 I=1,NTEMP,1
  II=I-1
  PHI=II*H/R
 SIG=E*ALPHA*(N*PI*R-PI*TEMP(I)+SIN(PHI)*SUM(2)+[illegible]
 1+COS(PHI)*[illegible]3))
  THETA=180.*PHI/PI
 PRINT*,THETA,TEMP[illegible]
0 CONTINUE
 STOP
 END
 SUBROUT[illegible]
 DIMENSION SUM(10),WK(10)
 COMMON R,H,TEMP(61)
 PHI=X/R
 N=X/H+1.5
 WK(1)=TEMP(N)/R
 WK(2)=SIN(PHI)*TEMP(N)/R
 WK(3)=COS(PHI)*TEMP(N)/R
 RETURN
 END
ND OF FILE-
```

NO RESTRAINT

NOTE: VALUES TAKEN FROM FOLLOWING PAGES







No constraint

1 block

```
-PLN2(IN=LN2STRS,DATA=LN2DAT)
1. 1. 1.
334.4027611044 -5.3395163121 -109.3804477497
0. -316. 54416.89538004
6.00127369152 -207. 37190.18163283
12.00254738306 -49. 12049.67839008
18.00382107458 22. 346.2225565801
24.00509476611 53. -3918.012613223
30.00636845764 68. -6073.002973062
36.00764214917 74. -6737.851827734
42.00891584069 77. -6872.76139836
48.01018953222 78. -6640.997725621
54.01146322375 78. -6206.3493360.4
60.01273691528 79. -5892.580490344
66.0140106068 79. -5385.873462597
72.01528429833 79. -4851.297181925
78.01655798986 79. -4294.69610747
84.01783168139 79. -3722.176053734
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n [illegible]

NO constr

3 slock's

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ILLEGAL CONTROL CARD.
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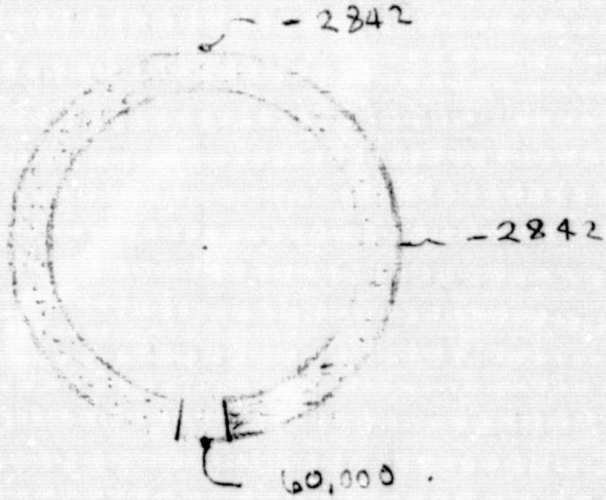
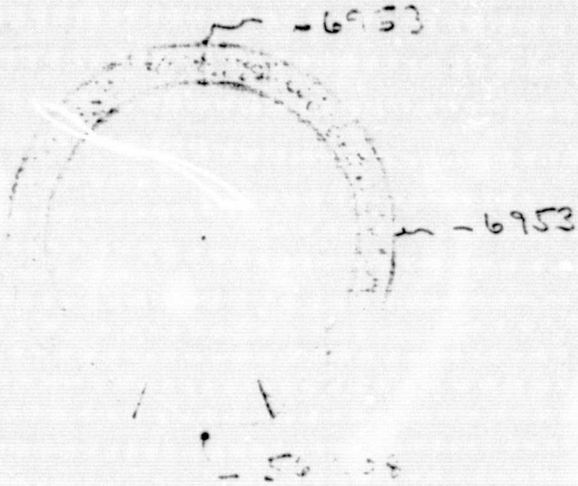
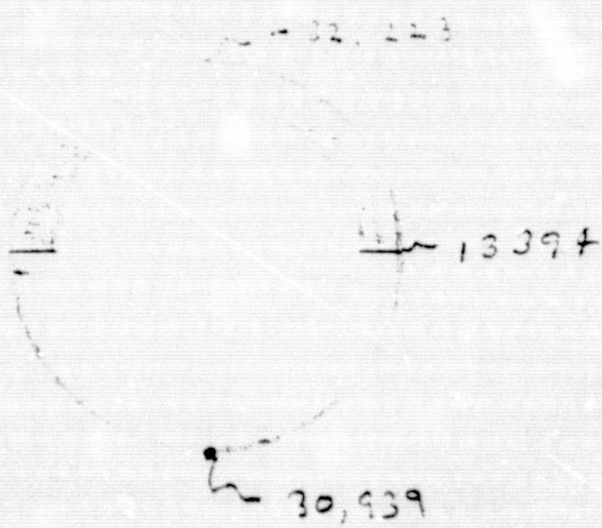
No constr
is slacks

BY ______ DATE ______ SUBJECT BE-YA THERMAL STRESSES IN SHELL SHEET NO. 51 OF ______
CHKD. BY ______ DATE ______ JOB NO. ______

CONSTRAINED IN BENDING ONLY







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Bending const o.k.

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ILLEGAL CONTROL CARD.
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Bending Constraint,
3 blocks

Bending Cons[illegible] 54

15 Slots)

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ILLEGAL CONTROL CARD.
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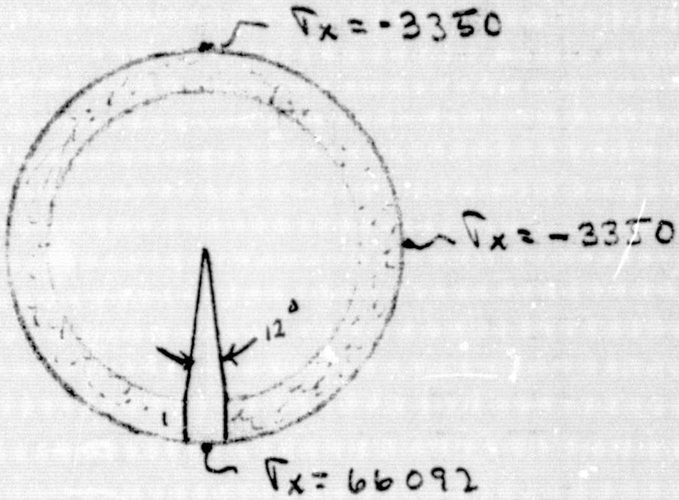
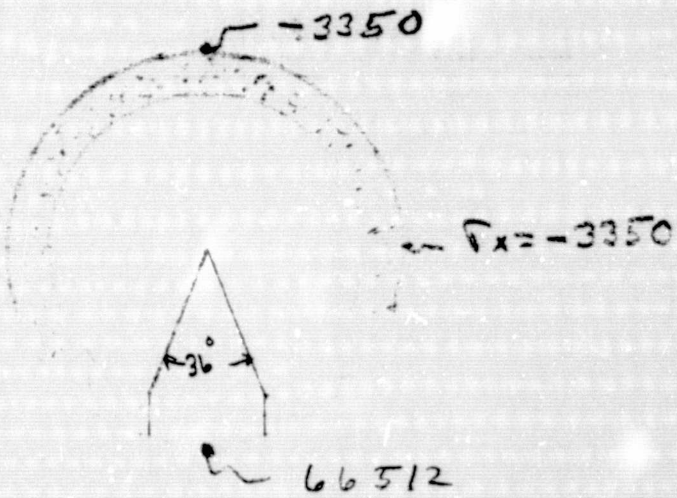
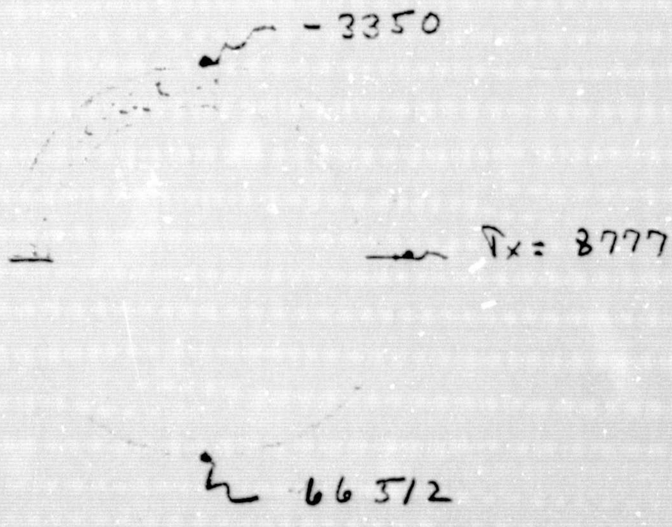
COMPLETELY RESTRAINED CYL.







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120.0254733306 79. -12600.5
126.0267475221 79. -12600.5
132.0280212136 79. -12600.5
138.0292949051 79. -12600.5
144.0305685967 79. -12600.5
150.0318422882 79. -12600.5
156.0331159797 79. -12600.5
162.0343896712 79. -12600.5
168.0356633628 79. -12600.5
174.0369370543 79. -12600.5
180.0382107458 79. -12600.5
186.0394844374 79. -12600.5
192.0407581289 79. -12600.5
198.0420318204 79. -12600.5
204.043305511[illegible] 79. -12600.5
210.044579203[illegible] 79. -12600.5
216.045852895 79. -12600.5
222.047126586[illegible] 79. -12600.5
228.048400278[illegible] 79. -12600.5
234.04967396[illegible] 79. -12600.5
240.050947661[illegible] 79. -12600.5
246.052221352[illegible] 79. -12600.5
252.053495044[illegible] 79. -12600.5
258.05476873[illegible] 79. -12600.5
264.05604242[illegible] 79. -12600.5
270.05731611[illegible] 79. -12600.5
276.0585898[illegible] 79. -12600.5
282.05986350[illegible] 79. -12600.5
288.0611371933 79. -12600.5
294.0624108849 79. -12600.5
300.0636845764 79. -12600.5
306.0649582679 79. -12600.5
312.0662319594 78. -12441.
318.067505651 78. -12441.
324.0687793425 77. -12281.5
330.070053034 74. -11803.
336.0713267256 68. -10846.
342.0726004171 53. -8453.5
348.0738741086 22. -3509.
354.0751478001 -49. 7815.5
360.0764214917 -207. 33016.5
 ILLEGAL CONTROL CARD.
/
```

completely constrained

(see note on next page)

```
0. -317. 50561.5
6.001273691528 -317. 50561.5
12.00254738306 -316. 50402.
18.00382107458 -207. 33016.5
24.00509476611 -49. 7815.5
30.00636845764 22. -3509.
36.00764214917 53. -8453.5
42.00891584069 68. -10846.
48.01018953222 74. -11803.
54.01146322375 77. -12281.5
60.01273691528 78. -12441.
66.0140106068 78. -12441.
72.01528429833 79. -12600.5
78.01655798986 79. -12600.5
84.01783168139 79. -12600.5
90.01910537292 79. -12600.5
96.02037906444 79. -12600.5
102.021652756 79. -12600.5
108.0229264475 79. -12600.5
114.024200139 79. -12600.5
120.0254738306 79. -12600.5
126.0267475221 79. -12600.5
132.0280212136 79. -12600.5
138.0292949051 79. -12600.5
144.0305685967 79. -12600.5
150.0318422882 79. -12600.5
156.0331159797 79. -12600.5
162.0343896712 79. -12600.5
168.0356633628 79. -12600.5
174.0369370543 79. -12600.5
180.0382107458 79. -12600.5
186.0394844374 79. -12600.5
192.0407581239 79. -12600.5
198.0420318204 79. -12600.5
204.0433055119 79. -12600.5
210.0445792035 79. -12600.5
216.045852895 79. -12600.5
222.0471265865 79. -12600.5
228.0484002781 79. -12600.5
234.0496739696 79. -12600.5
240.0509476611 79. -12600.5
246.0522213526 79. -12600.5
252.0534950442 79. -12600.5
258.0547687357 79. -12600.5
264.0560424272 79. -12600.5
270.0573161187 79. -12600.5
276.0585898103 79. -12600.5
282.0598635019 79. -12600.5
288.0611371933 79. -12600.5
294.0624108849 79. -12600.5
300.0636845764 78. -12441.
306.0649582679 78. -12441.
312.0662319594 77. -12281.5
318.067505651 74. -11803.
324.0687793425 68. -10846.
330.070053034 53. -8453.5
336.0713267256 22. -3509.
342.072600417 1 -49. 7815.5
348.0738741086 -207. 33016.5
354.0751478001 -316. 50402.
360.0764214917 -317. 50561.5
 ILLEGAL CONTROL CARD.
/new
```

completely constrained

Note I put in final Temps as if initial Temp was 0°

∴ stresses should be modified by

$$\frac{100-T}{T} \times \sigma$$

$\theta = 0$ $\left[\frac{100-(-317)}{317}\right] 50562 = 66512$

$\theta = 180$ $\left(\frac{100-79}{79}\right)(-12600.5) = [illegible]$

15 Blocks

completely constrained

same as above

see note above

```
0.  -317.  50561.5
6.0012731528 -317.  50561.5
12.0025473306 -317.  50561.5
18.0038210758 -317.  50561.5
24.0050947611 -317.  50561.5
30.0063684376 -317.  50561.5
36.0076421491 -317.  50561.5
42.0089158406 -317.  50561.5
48.0101895322 -317.  50561.5
54.0114632237 -317.  50561.5
60.0127369152 -317.  50561.5
66.0140106068 -317.  50561.5
72.0152842083 -317.  50561.5
78.0165579898 -317.  50561.5
84.0178316813 -316.  50402.
90.0191053729 -207.  33016.5
96.0203790644 -49.  7315.5
102.021652756 22.  -3500.
108.022926447 53.  [illegible]
114.02420013[illegible] 68.  [illegible]
120.0254733306 74.  -11803.
126.0267475221 77.  -12281.5
132.0280212136 78.  -12441.
138.0292949051 78.  -12441.
144.0305685967 79.  -12600.5
150.031842288[illegible] 79.  -12600.5
156.[illegible] 79.  -12600.5
162.[illegible]8967[illegible] 79.  -12600.5
168.[illegible] 79.  -12600.5
[illegible]
[illegible]
[illegible]
[illegible]
[illegible]
[illegible]
[illegible]
[illegible]
[illegible]
[illegible]
[illegible]
[illegible]
[illegible]
[illegible]
[illegible]
[illegible]
[illegible]
[illegible]
[illegible]
276.[illegible] -207. [illegible]
282.[illegible] -316. [illegible]
288.[illegible]
294.[illegible]
300.[illegible] -317. [illegible]
306.064[illegible] -317. 50561.5
312.0662311541 -317. 50561.5
318.067585651 -317. 50561.5
324.0687793425 -317. 50561.5
330.070053034 -317. 50561.5
336.0713267256 -317. 50561.5
342.072600417 -317. 50561.5
348.0738741086 -317. 50561.5
354.0751478001 -317. 50561.5
360.0764214917 -317. 50561.5
ILLEGAL CONTROL CARD.
```

BY ________ DATE ________ SUBJECT ________ SHEET NO. 57 OF ____
CHKD. BY ________ DATE ________ JOB NO. ________

The peak stresses are tensile stresses and they are proportional to the amount of end constraint on the cylinder. For the completely constrained cyl. the amount of exposed surface does not effect the peak stress. Whereas for the other two cases the more exposed shell – the lower the thermal stress. The boundary conditions that approximate the short leg best are the bending constraint only. This part of the tunnel is flexible in the axial direction. Therefore the peak tensile stress occurs with only a small exposed area and will have a maximum value of 60,000 psi. The compressive stress increases with increasing exposed area, For half of the shell exposed this stress is – 32,223 psi, need to check this for buckling. From ref 1

$\sigma_x)_{cr} = .606\,\gamma \dfrac{Et}{R}$ $\gamma \equiv$ Knock down factor

$\dfrac{R}{t} = \dfrac{96.66\,in}{.67\,in} = 144$ $\dfrac{L}{R} = \dfrac{25'}{8.33'} = 3.0$ ..

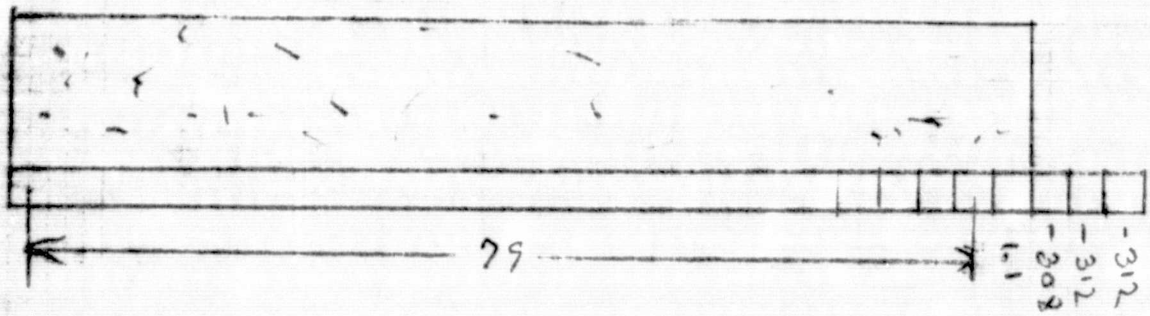
$\gamma = .28$

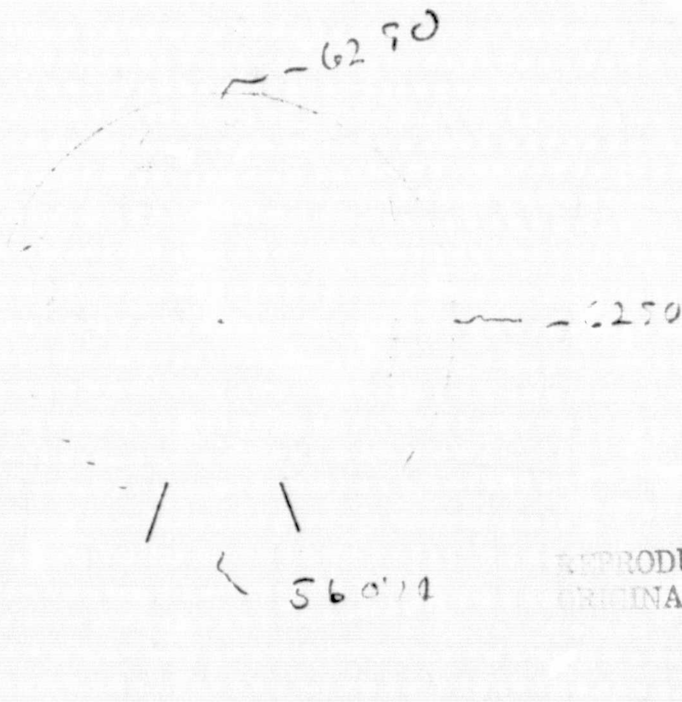
$\sigma_x)_{cr} = (.606)(.28)(29\times10^6).67/96.66 = 34,108$ psi

∴ for even half the shell exposed to LN2 or GN2 the compressive stress is less than critical.

TRANSIENT STRESSES FOR 3 BLOCKS

18" INSUL.





∴ Steady state is the worst thermal stress

6" INSULATION

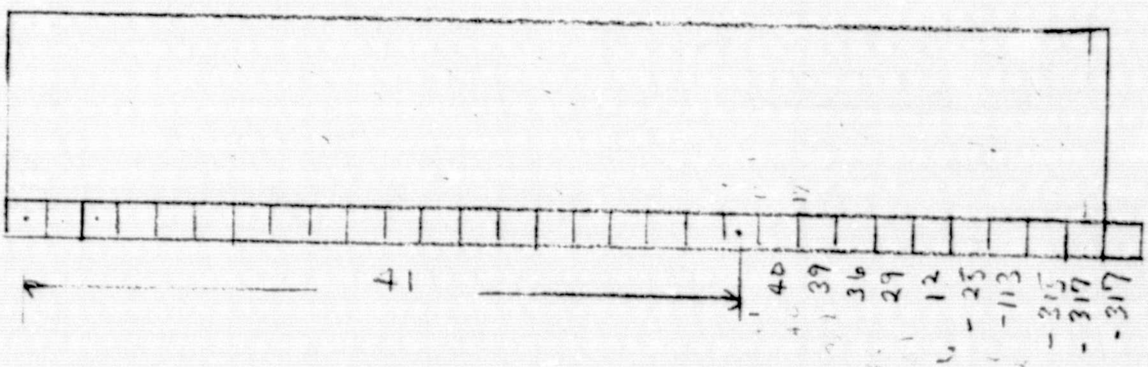
Check to see if 6" insulation yields higher thermal stresses than 18".

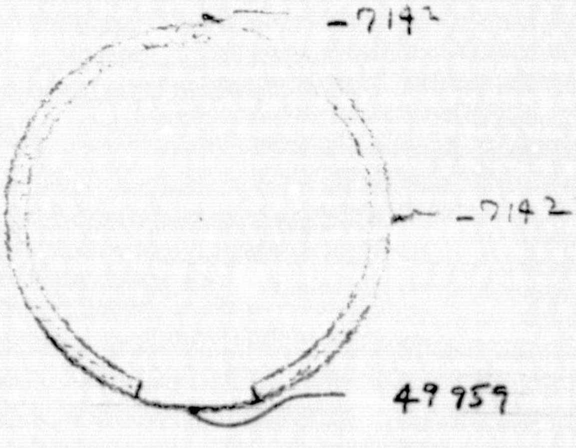
for insul shell $h_{eff} = \dfrac{1}{\dfrac{1}{1.387} + \dfrac{6 \times 144}{1.47}} = 1.7 \times 10^{-3}$

i.For Insul Blks:-

$h_{eff} = [1.7 \times 10^{-3} + 1.5/144]/2 = 6.059 \times 10^{-3}$

$T_{eff} = \dfrac{1.7 \times 10^{-3}(140) + (.01042)(560)}{2(.00549)} = 501\ ^\circ R$





∴ 18" INSULATION IS WORSE CASE

BY ________ DATE ______ SUBJECT ______________________ SHEET NO. 62 OF ______

CHKD. BY ______ DATE ______ ______________________ JOB NO. ______

FINITE ELEMENT MODEL.

The closed form solution is not valid near the ends and also assumes that hoop stresses are small compared to axial stresses. A right circular cyl., 25' long, was modeled to check these two points plus allows for complex accident simulation and complex structural geometry (reinforcing rings). A completely constrained model was run with half the cyl. exposed to GN2 flow. The results in the center of the cyl. (away from ends) agreed excellently; However much higher axial (factor of 2) stresses and hoop stresses existed near the ends. Also, a restrained in bending only model was run. The stresses in the middle did not agree with closed form (they were lower) and those at the ends were much higher. Therefore, end conditions are significant and the finite element model should be used to predict fatigue life.

BY	DATE	SUBJECT	SHEET NO. 63 OF
CHKD. BY	DATE		JOB NO.

RESULTS OF SPAR FINITE ELEMENT

THE 1 BLOCK CASE WAS RUN IN SPAR COMPUTER RUN NO. "EDQ."

THE MAXIMUM BENDING STRESS AT JOINT 496 (CORNER LOCATION) IS 99,640 psi

THE MEMBRANE STRESS AT THIS LOCATION IS 54,860 psi

THE 3 BLOCK CASE IN SHOWN IN RUN "DFZ".

THE 15 BLOCK CASE WAS RUN IN SPAR COMPUTER RUN NO. "ECK."

MAXIMUM BENDING STRESS AT JOINT 496 IS 127,110 psi

MEMBRANE STRESS IS 65,940 psi

THE MODEL AND RESULTS ARE SHOWN IN THE FOLLOWING PAGES. THE MAX. STRESSES OCCUR AT THE FIXED BOUNDARY CONDITIONS.

1 BLOCK @ -315°F

COMPUTER RUN C8 ≡

1/1/1

DISPLAY= SX /1000 , NODE= 4 , SURFACE= 0

0	0	0	0	0	0	0	0	0	0	0	2	-2	-16
0	0	0	0	0	0	0	0	0	0	0	2	-2	-16
0	0	0	0	0	0	0	0	0	0	0	2	-2	-16
0	0	0	0	0	0	0	0	0	0	0	2	-2	-16
0	0	0	0	0	0	0	0	0	0	0	2	-2	-16
0	0	0	0	0	0	0	0	0	0	0	2	-2	-16
0	0	0	0	0	0	0	0	0	0	0	2	-2	-16
0	0	0	0	0	0	0	0	0	0	0	2	-2	-16
0	0	0	0	0	0	0	0	0	0	0	2	-2	-16
0	0	0	0	0	0	0	0	0	0	0	2	-2	-16
0	0	0	0	0	0	0	0	0	0	0	2	-2	-16
0	0	0	0	0	0	0	0	0	0	0	2	-2	-16
0	0	0	0	0	0	0	0	0	0	0	2	-2	-16
0	0	0	0	0	0	0	0	0	0	0	2	-2	-16
0	0	0	0	0	0	0	0	0	0	0	2	-2	-16

SPEC 4.1

TOP HALF OF CYLINDER
THERMO LOADS

0 23
SCALE

)

DISPLAY= SX /1000 , NODE= 4, SURFACE= 1 1/1/1

0	0	0	0	0	0	0	0	0	0	0	2	1	-22
0	0	0	0	0	0	0	0	0	0	0	2	1	-22
0	0	0	0	0	0	0	0	0	0	0	2	1	-22
0	0	0	0	0	0	0	0	0	0	0	2	1	-22
0	0	0	0	0	0	0	0	0	0	0	2	1	-22
0	0	0	0	0	0	0	0	0	0	0	2	1	-22
0	0	0	0	0	0	0	0	0	0	0	2	1	-22
0	0	0	0	0	0	0	0	0	0	0	2	1	-22
0	0	0	0	0	0	0	0	0	0	0	2	1	-22
0	0	0	0	0	0	0	0	0	0	0	2	1	-22
0	0	0	0	0	0	0	0	0	0	0	2	1	-22
0	0	0	0	0	0	0	0	0	0	0	2	1	-22
0	0	0	0	0	0	0	0	0	0	0	2	1	-22
0	0	0	0	0	0	0	0	0	0	0	2	1	-22
0	0	0	0	0	0	0	0	0	0	0	2	1	-22

SPEC 4.1 TOP HALF OF CYLINDER
THERMO LOADS

0 ____ 23
SCALE

1 BLK
3 OF 17

1/1/1

DISPLAY= SX /1000 , NODE= 4, SURFACE= 2

0	0	0	0	0	0	0	0	0	0	0	2	-5	-11
0	0	0	0	0	0	0	0	0	0	0	2	-5	-11
0	0	0	0	0	0	0	0	0	0	0	2	-5	-11
0	0	0	0	0	0	0	0	0	0	0	2	-5	-11
0	0	0	0	0	0	0	0	0	0	0	2	-5	-11
0	0	0	0	0	0	0	0	0	0	0	2	-5	-11
0	0	0	0	0	0	0	0	0	0	0	2	-5	-11
0	0	0	0	0	0	0	0	0	0	0	2	-5	-11
0	0	0	0	0	0	0	0	0	0	0	2	-5	-11
0	0	0	0	0	0	0	0	0	0	0	2	-5	-11
0	0	0	0	0	0	0	0	0	0	0	2	-5	-11
0	0	0	0	0	0	0	0	0	0	0	2	-5	-11
0	0	0	0	0	0	0	0	0	0	0	2	-5	-11
0	0	0	0	0	0	0	0	0	0	0	2	-5	-11
0	0	0	0	0	0	0	0	0	0	0	2	-5	-11

0 ____ 2.
SCALE

SPEC 4.1

TOP HALF OF CYLINDER
THERMO LOADS

)

1/1/1

DISPLAY= SX /1000 , NODE= 4, SURFACE= 0

0	0	0	0	0	0	0	0	0	0	0	2	-2	-16
0	0	0	0	0	0	0	0	0	0	0	2	-2	-16
0	0	0	0	0	0	0	0	0	0	0	2	-2	-16
0	0	0	0	0	0	0	0	0	0	0	2	-2	-16
0	0	0	0	0	0	0	0	0	0	0	2	-2	-16
0	0	0	0	0	0	0	0	0	0	0	2	-2	-16
0	0	0	0	0	0	0	0	0	0	0	2	-2	-16
0	0	0	0	0	0	0	0	0	0	0	2	-2	-16
0	0	0	0	0	0	0	0	0	0	0	2	-2	-16
0	0	0	0	0	0	0	0	0	0	0	1	-2	-15
0	0	0	0	0	0	0	0	0	0	0	1	-1	-12
0	0	0	0	0	0	0	0	0	0	0	0	0	-8
0	0	0	0	0	0	0	0	0	0	0	-1	2	3
0	0	0	0	0	0	0	0	0	0	0	-3	3	26
0	0	0	0	0	0	0	0	0	0	0	-4	3	54

SPEC 5.1 BOTTOM HALF OF CYLINDER
THERMO LOADS

0
SCALE

1/1/1

DISPLAY= SX /1000 , NODE= 4, SURFACE= 1

0	0	0	0	0	0	0	0	0	0	0	2	1	-22
0	0	0	0	0	0	0	0	0	0	0	2	1	-22
0	0	0	0	0	0	0	0	0	0	0	2	1	-22
0	0	0	0	0	0	0	0	0	0	0	2	1	-22
0	0	0	0	0	0	0	0	0	0	0	2	1	-22
0	0	0	0	0	0	0	0	0	0	0	2	1	-22
0	0	0	0	0	0	0	0	0	0	0	2	1	-22
1	1	1	1	1	0	0	0	0	0	0	2	1	-22
1	1	1	1	1	1	1	1	1	0	0	2	2	-21
1	1	1	1	1	1	1	1	1	1	0	2	2	-20
0	0	0	0	1	1	1	1	1	1	1	2	3	-18
0	0	0	0	0	0	0	1	1	1	1	1	5	-13
0	0	0	0	0	0	0	0	0	0	1	-2	8	0
-1	-1	-1	-1	-1	-1	-1	-1	-1	-1	0	-6	6	29
-1	-1	-1	-1	-1	-1	-1	-1	-2	-2	-1	-8	-4	65

SPEC 5.1 BOTTOM HALF OF CYLINDER
THERMO LOADS

0 SCALE

)

DISPLAY= SX /1000 , NODE= 4, SURFACE= 2

1/1/1

0	0	0	0	0	0	0	0	0	0	0	2	-5	-11
0	0	0	0	0	0	0	0	0	0	0	2	-5	-11
0	0	0	0	0	0	0	0	0	0	0	2	-5	-11
0	0	0	0	0	0	0	0	0	0	0	2	-5	-11
0	0	0	0	0	0	0	0	0	0	0	2	-5	-11
0	0	0	0	0	0	0	0	0	0	0	2	-5	-11
0	0	0	0	0	0	0	0	0	0	0	2	-5	-11
-1	-1	-1	-1	-1	-1	0	0	0	0	0	2	-6	-10
-1	-1	-1	-1	-1	-1	-1	-1	-1	-1	0	1	-5	-10
-1	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1	1	-5	-9
0	0	0	0	-1	-1	-1	-1	-1	-1	-1	0	-6	-7
0	0	0	0	0	0	0	-1	-1	-1	-2	0	-6	-2
0	0	0	0	0	0	0	0	0	0	-1	0	-4	6
1	1	1	1	1	1	1	1	1	1	0	1	1	24
1	1	1	1	1	1	1	1	2	2	2	1	10	43

SPEC 5.1

BOTTOM HALF OF CYLINDER
THERMO LOADS

0 23
SCALE

1/1/1

DISPLAY= SY /1000 , NODE= 4 , SURFACE= 0

-13	-13	-13	-13	-13	-13	-13	-13	-13	-13	-13	-13	-13	-13
-13	-13	-13	-13	-13	-13	-13	-13	-13	-13	-13	-13	-13	-13
-13	-13	-13	-13	-13	-13	-13	-13	-13	-13	-13	-13	-13	-13
-13	-13	-13	-13	-13	-13	-13	-13	-13	-13	-13	-13	-13	-13
-13	-13	-13	-13	-13	-13	-13	-13	-13	-13	-13	-13	-13	-13
-13	-13	-13	-13	-13	-13	-13	-13	-13	-13	-13	-13	-13	-13
-13	-13	-13	-13	-13	-13	-13	-13	-13	-13	-13	-13	-13	-13
-13	-13	-13	-13	-13	-13	-13	-13	-13	-13	-13	-13	-13	-13
-13	-13	-13	-13	-13	-13	-13	-13	-13	-13	-13	-13	-13	-13
-13	-13	-13	-13	-13	-13	-13	-13	-13	-13	-13	-13	-13	-13
-13	-13	-13	-13	-13	-13	-13	-13	-13	-13	-13	-13	-13	-13
-13	-13	-13	-13	-13	-13	-13	-13	-13	-13	-1[illegible]	-13	-13	-13
-13	-13	-13	-13	-13	-13	-13	-13	-13	-13	-13	-13	-13	-13
-13	-13	-13	-13	-13	-13	-13	-13	-13	-13	-13	-13	-13	-13
-13	-13	-13	-13	-13	-13	-13	-13	-13	-13	-13	-13	-13	-13

SPEC 4.1

TOP HALF OF CYLINDER
THERMO LOADS

0 SCALE 2

1 BLK

8 OF 17

1/1/1

DISPLAY= SY /1000 , NODE= 4 , SURFACE= 1

-13	-13	-13	-13	-13	-13	-13	-13	-13	-13	-14	-12	-3	-32
-13	-13	-13	-13	-13	-13	-13	-13	-13	-13	-14	-12	-3	-32
-13	-13	-13	-13	-13	-13	-13	-13	-13	-13	-14	-12	-3	-32
-13	-13	-13	-13	-13	-13	-13	-13	-13	-13	-14	-12	-3	-32
-13	-13	-13	-13	-13	-13	-13	-13	-13	-13	-14	-12	-3	-32
-13	-13	-13	-13	-13	-13	-13	-13	-13	-13	-14	-12	-3	-32
-13	-13	-13	-13	-13	-13	-13	-13	-13	-13	-14	-12	-3	-32
-13	-13	-13	-13	-13	-13	-13	-13	-13	-13	-14	-12	-3	-32
-13	-13	-13	-13	-13	-13	-13	-13	-13	-13	-14	-12	-3	-32
-13	-13	-13	-13	-13	-13	-13	-13	-13	-13	-14	-12	-3	-32
-13	-13	-13	-13	-13	-13	-13	-13	-13	-13	-14	-12	-3	-32
-13	-13	-13	-13	-13	-13	-13	-13	-13	-13	-14	-12	-3	-32
-13	-13	-13	-13	-13	-13	-13	-13	-13	-13	-14	-12	-3	-32
-13	-13	-13	-13	-13	-13	-13	-13	-13	-13	-14	-12	-3	-32
-13	-13	-13	-13	-13	-13	-13	-13	-13	-13	-14	-12	-3	-32

PEC
4.1

TOP HALF OF CYLINDER
THERMO LOADS

0 23
SCALE

DISPLAY= SY /1000 , NODE= 4 , SURFACE= 2

-13	-13	-13	-13	-13	-13	-13	-13	-13	-13	-12	-13	-23	6
-13	-13	-13	-13	-13	-13	-13	-13	-13	-13	-12	-13	-23	6
-13	-13	-13	-13	-13	-13	-13	-13	-13	-13	-12	-13	-23	6
-13	-13	-13	-13	-13	-13	-13	-13	-13	-13	-12	-13	-23	6
-13	-13	-13	-13	-13	-13	-13	-13	-13	-13	-12	-13	-23	6
-13	-13	-13	-13	-13	-13	-13	-13	-13	-13	-12	-13	-23	6
-13	-13	-13	-13	-13	-13	-13	-13	-13	-13	-12	-13	-23	6
-13	-13	-13	-13	-13	-13	-13	-13	-13	-13	-12	-13	-23	6
-13	-13	-13	-13	-13	-13	-13	-13	-13	-13	-12	-13	-23	6
-13	-13	-13	-13	-13	-13	-13	-13	-13	-13	-12	-13	-23	6
-13	-13	-13	-13	-13	-13	-13	-13	-13	-13	-12	-13	-23	6
-13	-13	-13	-13	-13	-13	-13	-13	-13	-13	-12	-13	-23	6
-13	-13	-13	-13	-13	-13	-13	-13	-13	-13	-12	-13	-23	6
-13	-13	-13	-13	-13	-13	-13	-13	-13	-13	-12	-13	-23	6
-13	-13	-13	-13	-13	-13	-13	-13	-13	-13	-12	-13	-23	6

SPEC 4.1 TOP HALF OF CYLINDER
THERMO LOADS

0 SCALE

)

1/1/:

DISPLAY= SY /1000 , NODE= 4, SURFACE= 0

-13	-13	-13	-13	-13	-13	-13	-13	-13	-13	-13	-13	-13	-13
-13	-13	-13	-13	-13	-13	-13	-13	-13	-13	-13	-13	-13	-13
-13	-13	-13	-13	-13	-13	-13	-13	-13	-13	-13	-13	-13	-13
-13	-13	-13	-13	-13	-13	-13	-13	-13	-13	-13	-13	-13	-13
-13	-13	-13	-13	-13	-13	-13	-13	-13	-13	-13	-13	-13	-13
-13	-13	-13	-13	-13	-13	-13	-13	-13	-13	-13	-13	-13	-13
-13	-13	-13	-13	-13	-13	-13	-13	-13	-13	-13	-13	-13	-13
-13	-13	-13	-13	-13	-13	-13	-13	-13	-13	-13	-13	-13	-13
-13	-13	-13	-13	-13	-12	-12	-12	-12	-12	-12	-12	-12	-12
-12	-12	-12	-12	-12	-12	-12	-12	-12	-12	-12	-12	-12	-12
-11	-11	-11	-11	-11	-11	-11	-11	-11	-11	-11	-11	-11	-10
-9	-9	-9	-9	-9	-9	-9	-9	-9	-9	-9	-9	-8	-7
-3	-3	-3	-3	-3	-3	-3	-4	-4	-4	-4	-4	-4	-2
8	8	8	8	8	8	8	8	8	8	8	8	7	10
33	33	33	33	33	33	33	33	33	33	33	33	33	34

0 33
SCALE

SPEC 5.1 BOTTOM HALF OF CYLINDER
THERMO LOADS

1 BLK

11 OF 17

1/1/

DISPLAY= SY /1000 , NODE= 4, SURFACE= 1

-13	-13	-13	-13	-13	-13	-13	-13	-13	-13	-14	-12	-3	-32
-13	-13	-13	-13	-13	-13	-13	-13	-13	-13	-14	-12	-3	-32
-13	-13	-13	-13	-13	-13	-13	-13	-13	-13	-14	-12	-3	-32
-13	-13	-13	-13	-13	-13	-13	-13	-13	-13	-14	-12	-3	-32
-13	-13	-13	-13	-13	-13	-13	-13	-13	-13	-14	-13	-3	-32
-13	-13	-13	-13	-13	-13	-13	-13	-13	-13	-14	-13	-3	-32
-12	-12	-13	-13	-13	-13	-13	-13	-13	-13	-14	-12	-3	-32
-12	-12	-12	-12	-12	-12	-12	-12	-12	-12	-13	-12	-3	-31
-12	-12	-12	-12	-12	-12	-12	-12	-12	-12	-13	-12	-3	-31
-12	-12	-12	-12	-12	-12	-12	-12	-12	-11	-12	-11	-3	-29
-11	-11	-11	-11	-11	-11	-11	-11	-11	-10	-11	-10	-2	-26
-9	-9	-9	-9	-9	-9	-9	-9	-9	-8	-8	-8	-2	-17
-4	-4	-4	-4	-4	-4	-4	-4	-4	-4	-3	-5	-2	-1
8	8	8	8	8	8	8	8	8	7	9	5	-1	30
33	33	33	33	33	33	33	33	33	33	35	31	11	75

SPEC 5.1 BOTTOM HALF OF CYLINDER
THERMO LOADS

0 SCALE

)

1/1/1

DISPLAY= SY /1000 , NODE= 4, SURFACE= 2

-13	-13	-13	-13	-13	-13	-13	-13	-13	-13	-12	-13	-23	6
-13	-13	-13	-13	-13	-13	-13	-13	-13	-13	-12	-13	-23	6
-13	-13	-13	-13	-13	-13	-13	-13	-13	-13	-12	-13	-23	6
-13	-13	-13	-13	-13	-13	-13	-13	-13	-13	-12	-13	-23	6
-13	-13	-13	-13	-13	-13	-13	-13	-13	-13	-12	-13	-23	6
-13	-13	-13	-13	-13	-13	-13	-13	-13	-13	-12	-13	-23	6
-13	-13	-13	-13	-13	-13	-13	-13	-13	-13	-12	-13	-23	6
-13	-13	-13	-13	-13	-13	-13	-13	-13	-13	-12	-13	-22	6
-13	-13	-13	-13	-13	-13	-13	-13	-13	-13	-12	-13	-22	6
-12	-12	-12	-12	-12	-12	-12	-12	-12	-12	-11	-12	-21	6
-11	-11	-11	-11	-11	-11	-11	-11	-11	-11	-11	-11	-19	5
-9	-9	-9	-9	-9	-9	-9	-9	-9	-9	-9	-9	-15	3
-3	-3	-3	-3	-3	-3	-3	-3	-3	-4	-4	-3	-6	-3
8	8	8	8	8	8	8	8	8	8	7	10	16	-9
34	34	34	34	34	34	34	34	34	34	32	36	55	-7

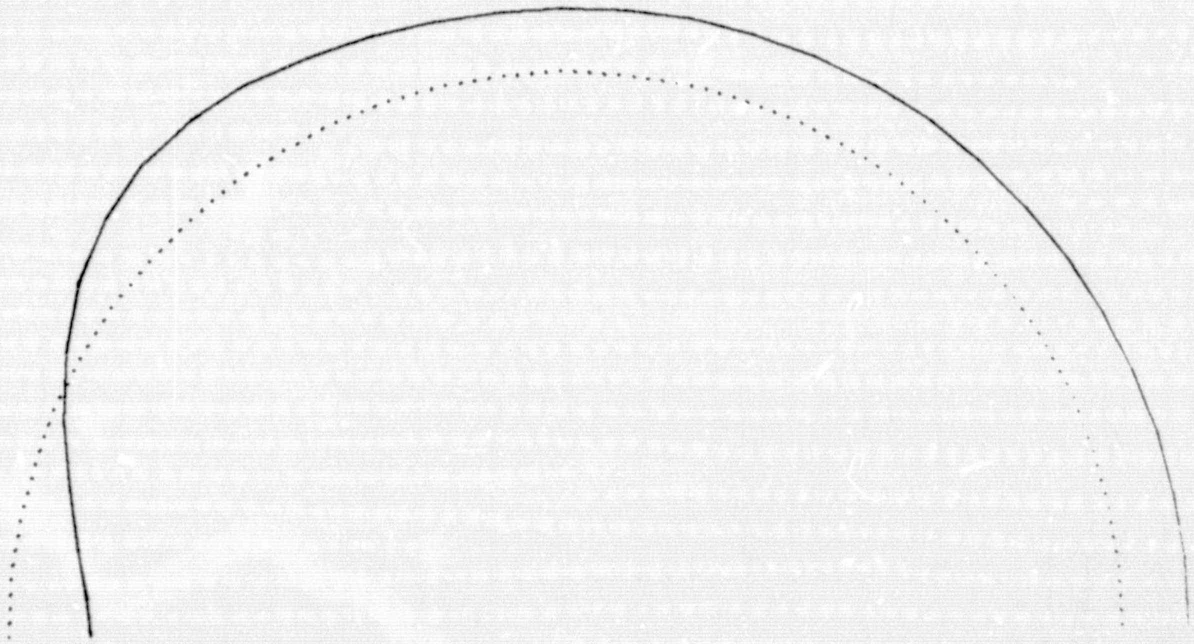
SPEC
5.1

BOTTOM HALF OF CYLINDER
THERMO LOADS

0 2[illegible]
SCALE

1 BLK
13 OF 17

1/1/1

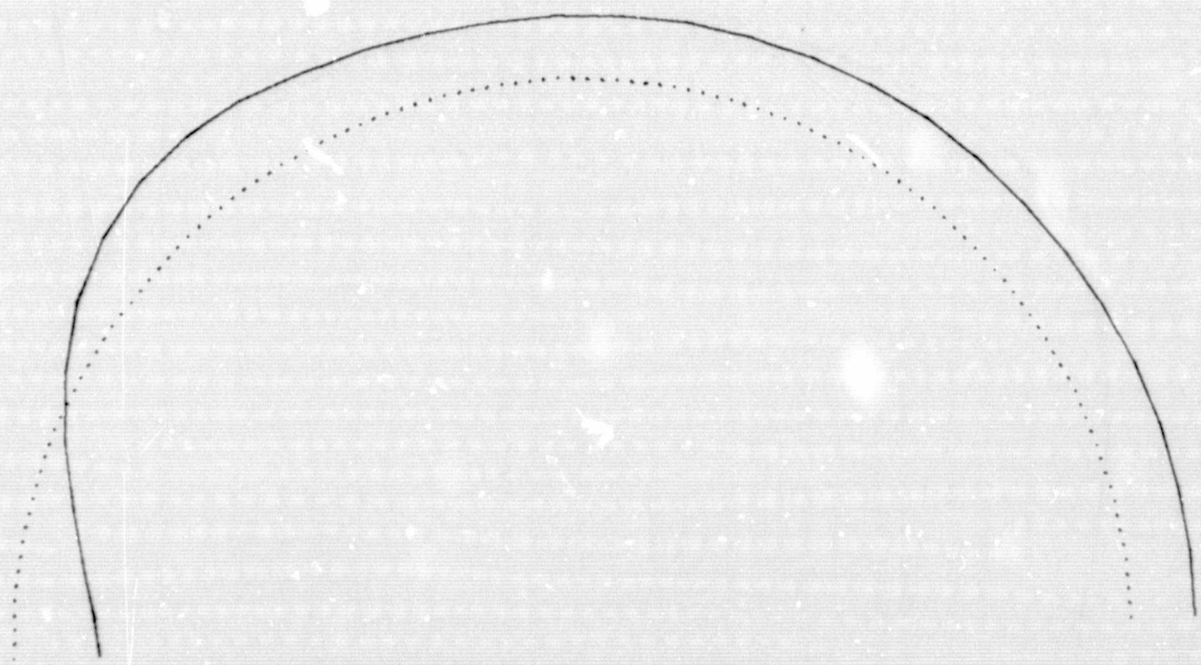


SPEC 2.1 RING

0 SCALE

1 BLK
14 OF 17

1/1/1

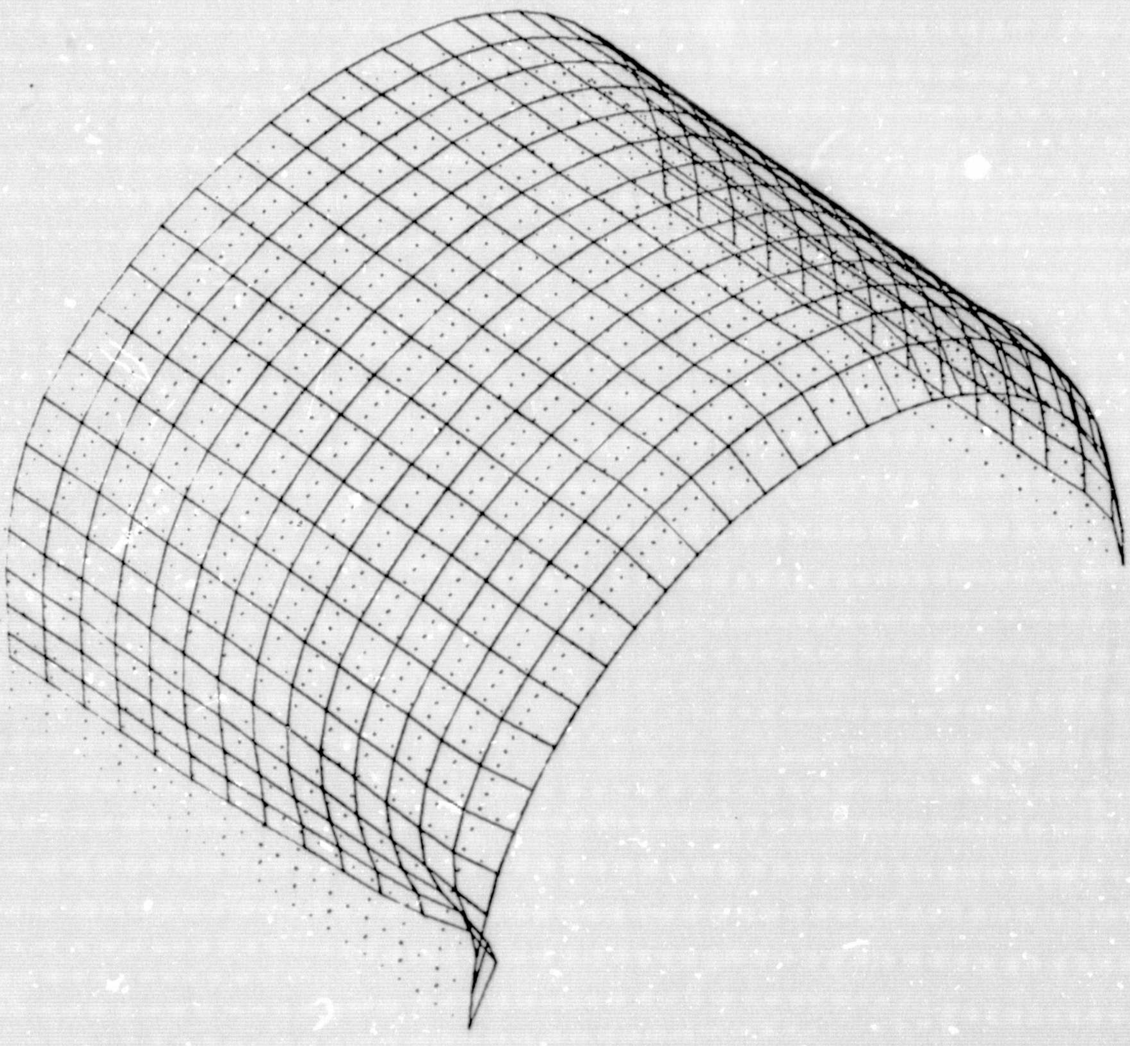


0 35
SCALE

C RING

1 BLK
15 OF 17

1/1/1



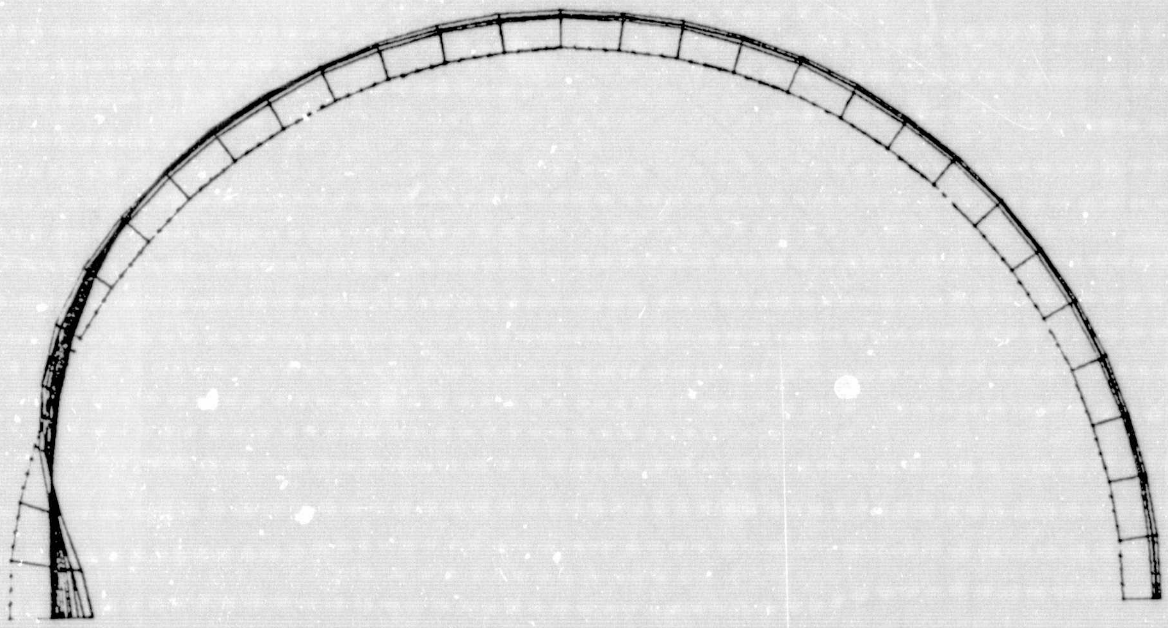
PEC
.1

ALL

0 42
SCALE

1 BLK
16 OF 17

1/1/1

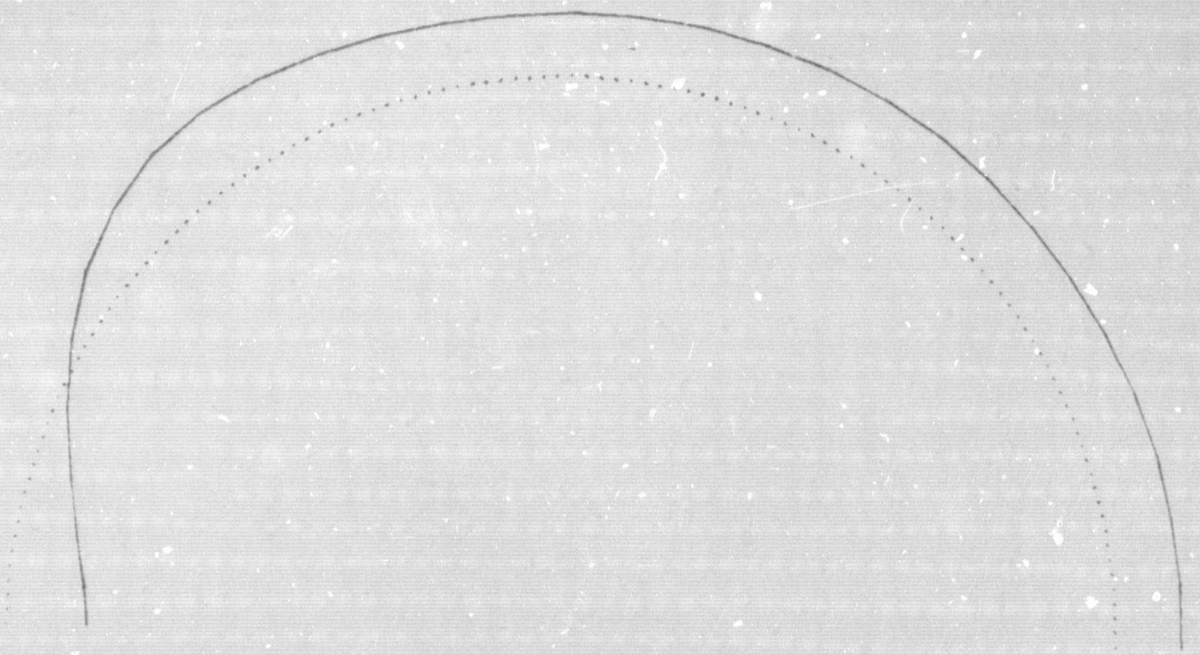


SPEC 7.1 ALL

0 35
SCALE

1 BLK
17 OF 17

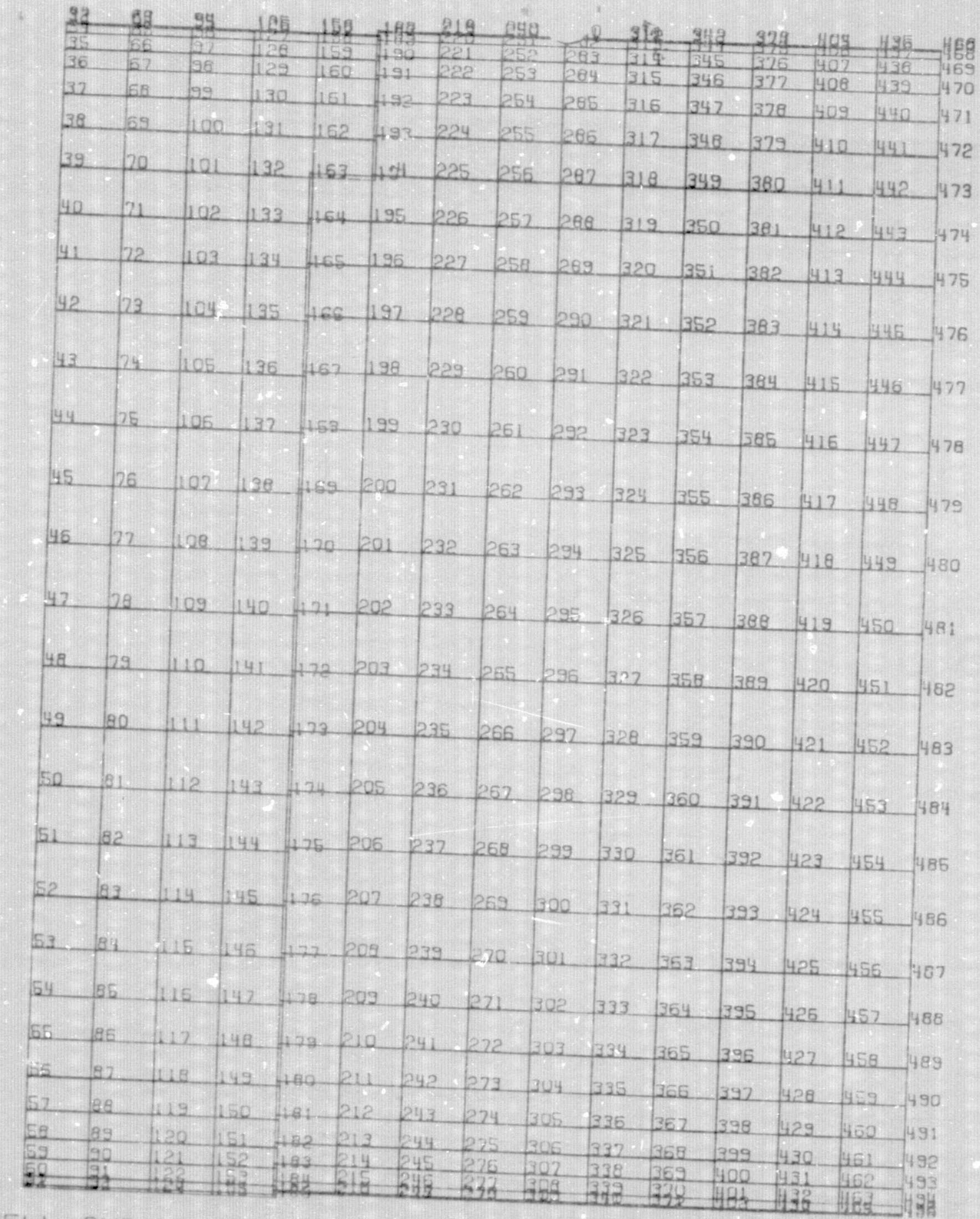
1/1/1



SPEC
2.1

ING

0 SCALE 35

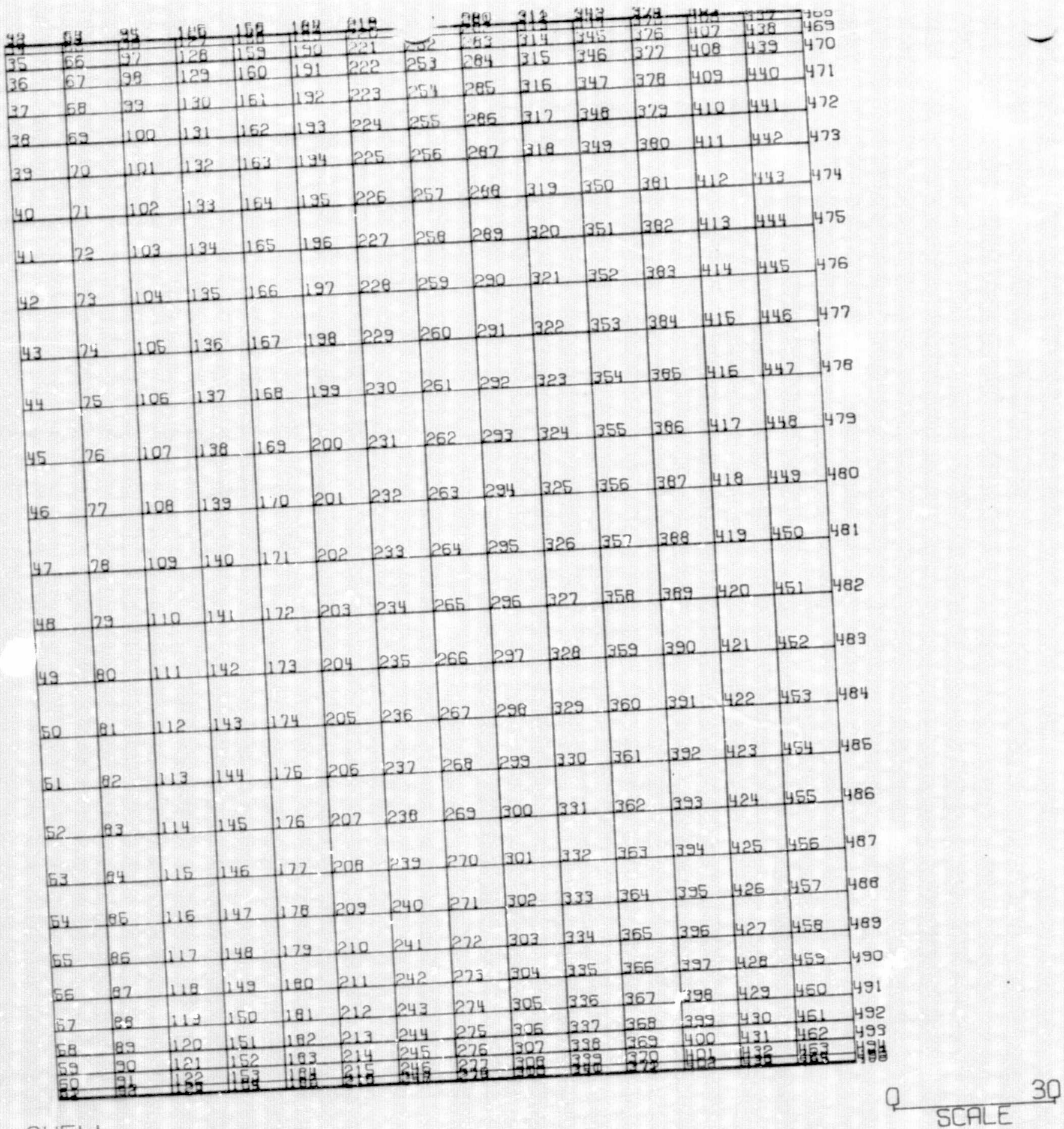


SPEC
1.1

SHELL AND RING ....ALL....

0 SCALE 30

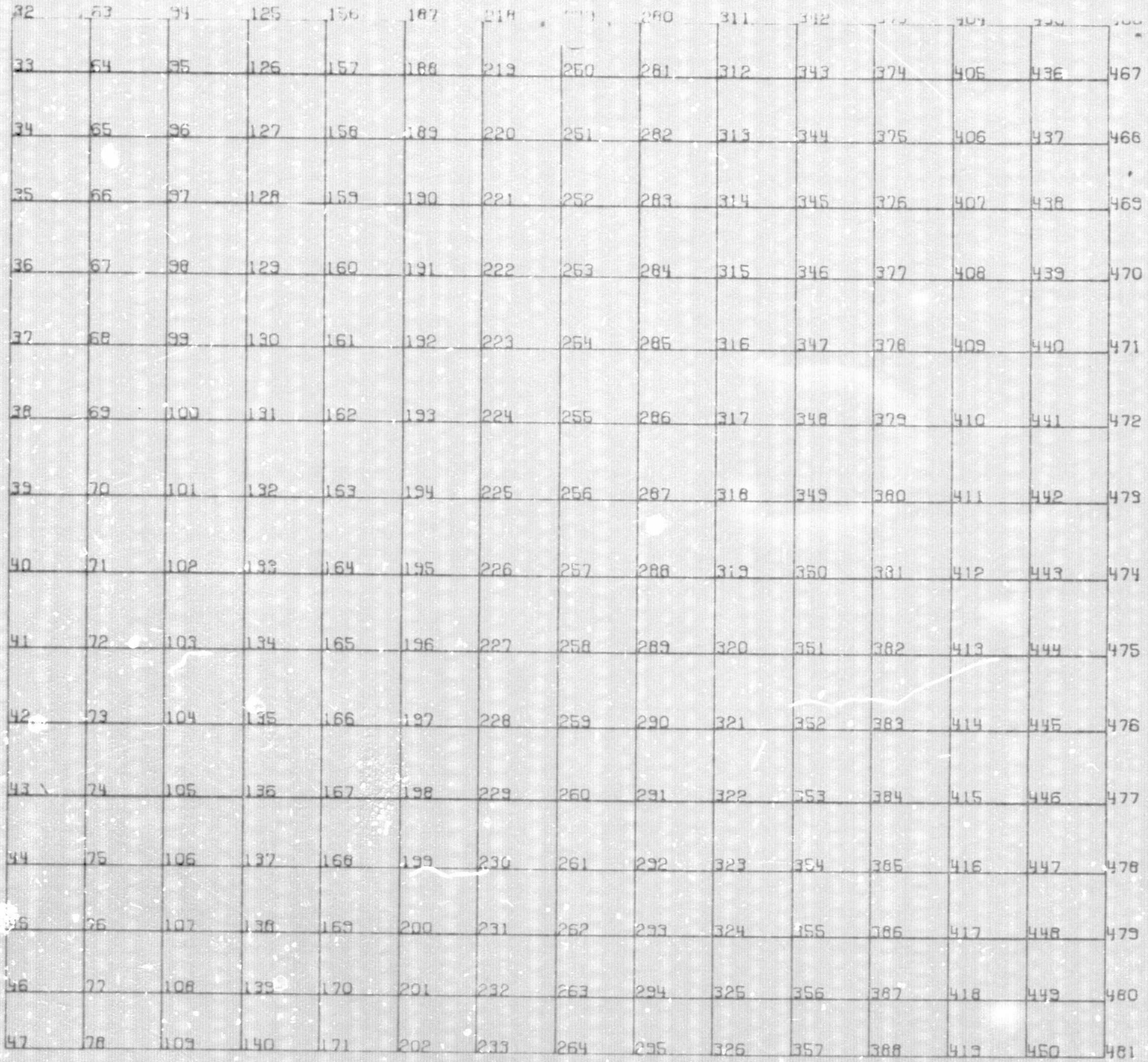
3 BLK CASE
RUN "DF2"
1 OF 21



SPEC
3.1

SHELL

3 BLK
2 OF 21



SPEC
4.1

TOP HALF OF CYLINDER
THERMO LOADS

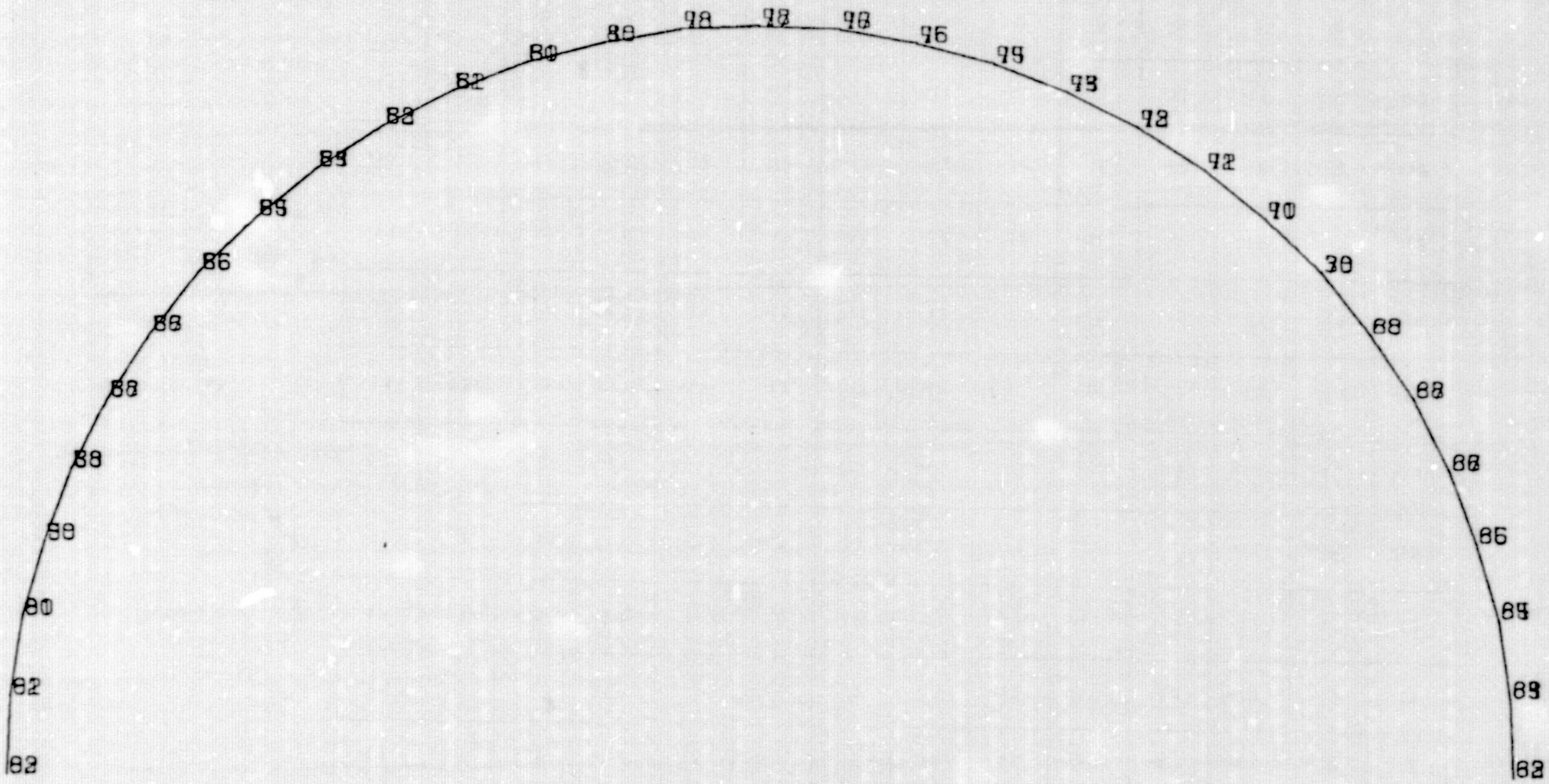
0 23
SCALE

3 BLK
3 OF

47	78	109	140	171	202	233	264	295	326	357	388	419	450	481
48	79	110	141	172	203	234	265	296	327	358	389	420	451	482
49	80	111	142	173	204	235	266	297	328	359	390	421	452	483
50	81	112	143	174	205	236	267	298	329	360	391	422	453	484
51	82	113	144	175	206	237	268	299	330	361	392	423	454	485
52	83	114	145	176	207	238	269	300	331	362	393	424	455	486
53	84	115	146	177	208	239	270	301	332	363	394	425	456	487
54	85	116	147	178	209	240	271	302	333	364	395	426	457	488
55	86	117	148	179	210	241	272	303	334	365	396	427	458	489
56	87	118	149	180	211	242	273	304	335	366	397	428	459	490
57	88	119	150	181	212	243	274	305	336	367	398	429	460	491
58	89	120	151	182	213	244	275	306	337	368	399	430	461	492
59	90	121	152	183	214	245	276	307	338	369	400	431	462	493
60	91	122	153	184	215	246	277	308	339	370	401	432	463	494
61	92	123	154	185	216	247	278	309	340	371	402	433	464	495
62	93	124	155	186	217	248	279	310	341	372	403	434	465	496

3 BLK
4 OF

23



3 BLK
5 OF 21

DISPLAY= SY /1000 . NODE= 4 . SURFACE= 0

-13	-13	-13	-13	-13	-13	-13	-13	-13	-13	-13	-13	-13	-13
-13	-13	-13	-13	-13	-13	-13	-13	-13	-13	-13	-13	-13	-13
-13	-13	-13	-13	-13	-13	-13	-13	-13	-13	-13	-13	-13	-13
-13	-13	-13	-13	-13	-13	-13	-13	-13	-13	-13	-13	-13	-13
-13	-13	-13	-13	-13	-13	-13	-13	-13	-13	-13	-13	-13	-13
-13	-13	-13	-13	-13	-13	-13	-13	-13	-13	-13	-13	-13	-13
-13	-13	-13	-13	-13	-13	-13	-13	-13	-13	-13	-13	-13	-13
-13	-13	-13	-13	-13	-13	-13	-13	-13	-13	-13	-13	-13	-13
-13	-13	-13	-13	-13	-13	-13	-13	-13	-13	-13	-13	-13	-13
-13	-13	-12	-12	-12	-12	-12	-12	-12	-12	-12	-12	-13	-12
-12	-12	-12	-12	-12	-12	-12	-12	-12	-12	-12	-12	-12	-12
-11	-11	-11	-11	-11	-11	-11	-11	-11	-11	-11	-11	-11	-10
-9	-9	-9	-9	-9	-9	-9	-9	-9	-9	-9	-9	-8	-7
-3	-3	-3	-3	-3	-3	-4	-4	-4	-4	-4	-4	-4	-2
8	3	8	8	8	8	8	8	8	8	8	8	8	10

0 23
.SCALE

SPEC
4.1

TOP HALF OF CYLINDER
THERMO LOADS

3 BLK
6 OF 21

DISPLAY= SX /1000 . NODE= 4. SURFACE= 1

0	0	0	0	0	0	0	0	-1	0	0	-8	1	64
0	0	0	-1	-1	-1	-1	-1	-1	-1	0	-10	-4	83
-1	-1	-1	-1	-1	-1	-1	-1	-1	-1	0	-10	-5	87
-1	-1	-1	-1	-1	-1	-1	-1	-1	-1	0	-9	-6	88
-1	-1	-1	-1	-1	-1	-1	-1	-1	0	1	-8	-4	89
-1	-1	-1	-1	-1	-1	-1	0	-1	0	1	-7	-4	89
0	0	0	0	0	0	0	0	0	0	1	-7	-4	89
0	0	0	0	0	0	0	0	0	0	1	-7	-4	89
0	0	0	0	0	0	0	0	0	1	1	-7	-4	89
0	0	0	0	0	0	0	0	0	0	1	-7	-4	89
0	0	0	0	0	0	0	0	0	0	1	-7	-4	89
0	0	0	0	0	0	0	0	0	0	1	-7	-4	89
0	0	0	0	0	0	0	0	0	0	1	-7	-4	89
0	0	0	0	0	0	0	0	0	0	1	-7	-4	89
0	0	0	0	0	0	0	0	0	0	1	-7	-4	89

3 BLK
7 OF 21

SPEC BOTTOM HALF OF CYLINDER.

0 23
SCALE

DISPLAY= SX /1000 . NODE= 4. SURFACE= 2

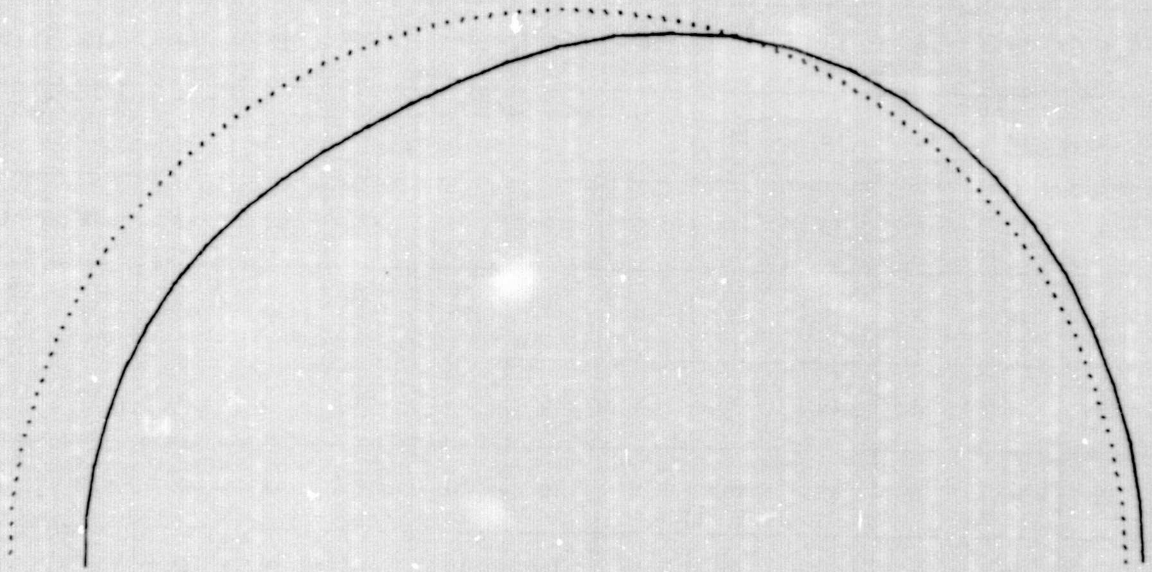
0	0	0	0	0	0	0	0	0	1	0	-1	8	45
0	0	1	1	1	1	1	1	1	2	1	-2	16	49
1	1	1	1	1	1	1	1	1	2	1	-4	20	45
1	1	1	1	1	1	1	1	1	2	0	-5	20	43
1	1	1	1	1	1	1	1	1	1	0	-6	20	43
1	1	1	1	1	1	1	0	0	1	-1	-6	20	43
0	0	0	0	0	0	0	0	0	1	-1	-6	20	43
0	0	0	0	0	0	0	0	0	1	-1	-6	20	43
0	0	0	0	0	0	0	0	0	1	-1	-6	20	43
0	0	0	0	0	0	0	0	0	1	-1	-6	20	43
0	0	0	0	0	0	0	0	0	1	-1	-6	20	43
0	0	0	0	0	0	0	0	0	1	-1	-6	20	43
0	0	0	0	0	0	0	0	0	1	-1	-6	20	43
0	0	0	0	0	0	0	0	0	1	-1	-6	20	43
0	0	0	0	0	0	0	0	0	1	-1	-6	20	43

0 23
SCALE

SPEC
5.1

BOTTOM HALF OF CYLINDER
THERMO LOADS

3 BLK
3 OF 21



SPEC
7.1

ALL

0 35
SCALE

3 BLK
9 of 21

DISPLAY= SY /1000 , NODE= 4 , SURFACE= 0

33	33	33	33	33	33	33	33	33	33	33	33	34	35
61	61	61	61	61	61	61	61	61	61	61	61	62	61
61	61	61	61	61	61	61	61	61	61	61	61	61	61
61	61	61	61	61	61	61	61	61	61	61	61	61	61
61	61	61	61	61	61	61	61	61	61	61	61	61	61
61	61	61	61	61	61	61	61	61	61	61	61	61	61
61	61	61	61	61	61	61	61	61	61	61	61	61	61
61	61	61	61	61	61	61	61	61	61	61	61	61	61
61	61	61	61	61	61	61	61	61	61	61	61	61	61
61	61	61	61	61	61	61	61	61	61	61	61	61	61
61	61	61	61	61	61	61	61	61	61	61	61	61	61
61	61	61	61	61	61	61	61	61	61	61	61	61	61
61	61	61	61	61	61	61	61	61	61	61	61	61	61
61	61	61	61	61	61	61	61	61	61	61	61	61	61
61	61	61	61	61	61	61	61	61	61	61	61	61	61

3 BLK
10 OF 21

SPEC 5.1 BOTTOM HALF OF CYLINDER THERMO LOADS

0 23 SCALE

DISPLAY= SY /1000 , NODE= 4 , SURFACE= 1

33	33	33	33	33	33	33	33	33	33	35	31	12	78
61	61	61	61	61	61	61	61	61	61	64	49	18	114
61	61	61	61	61	61	61	61	61	61	64	49	13	123
61	61	61	61	61	61	61	61	61	61	64	49	11	127
61	61	61	61	61	61	61	61	61	61	65	60	11	128
61	61	61	61	61	61	61	61	61	61	65	60	12	128
61	61	61	61	61	61	61	61	61	61	65	60	12	127
61	61	61	61	61	61	61	61	61	61	66	60	12	127
61	61	61	61	61	61	61	61	61	61	66	60	12	127
61	61	61	61	61	61	61	61	61	61	66	60	12	127
61	61	61	61	61	61	61	61	61	61	65	60	12	127
61	61	61	61	61	61	61	61	61	61	65	60	12	127
61	61	61	61	61	61	61	61	61	61	66	60	12	127
61	61	61	61	61	61	61	61	61	61	65	60	12	127
61	61	61	61	61	61	61	61	61	61	66	60	12	127

3 BLK
11 OF 21

SPEC BOTTOM HALF OF CYLINDER
THERMO LOADS

0 23
SCALE

DISPLAY= SY /1000 . NODE= 4. SURFACE= 2

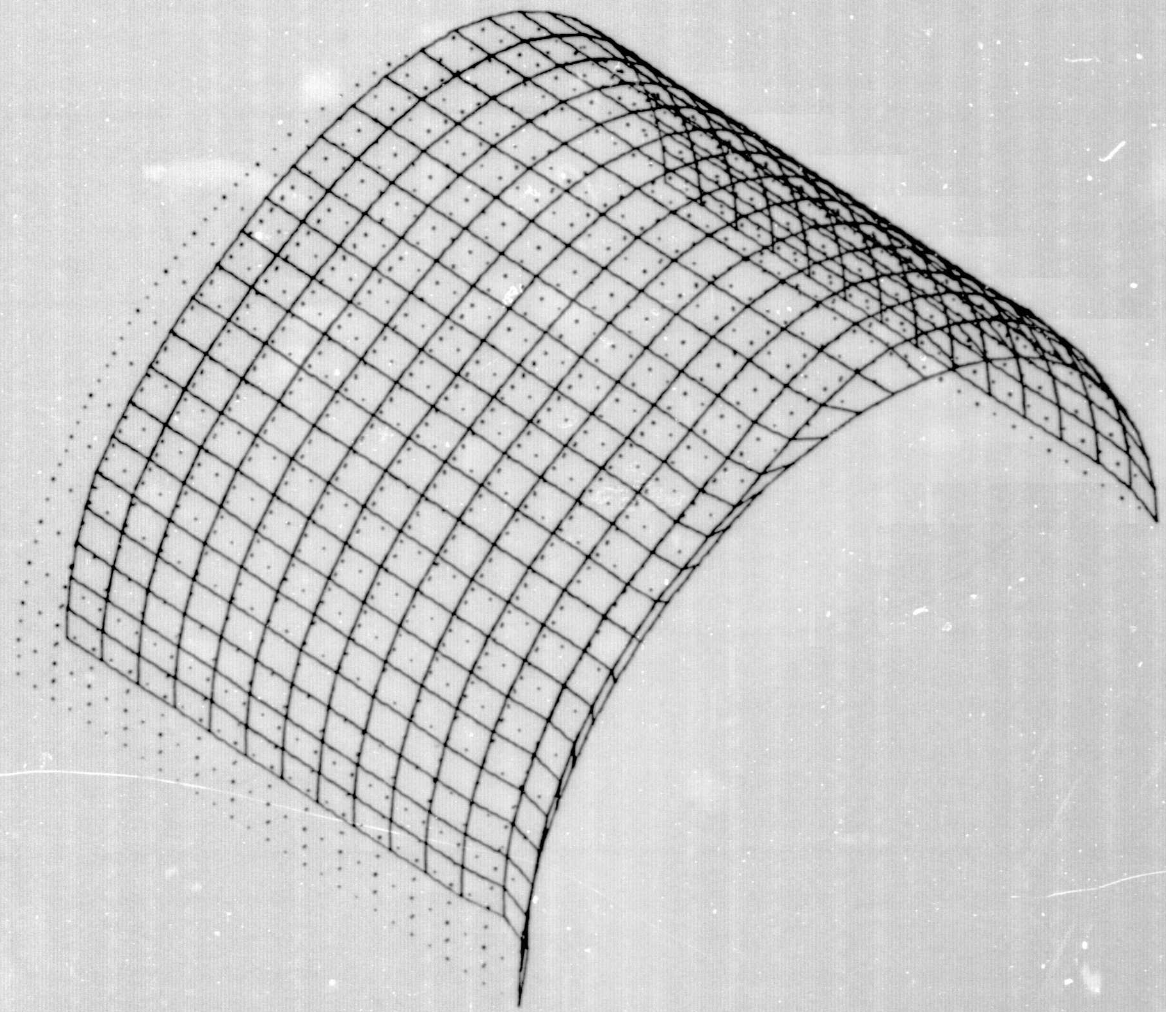
33	33	33	33	33	34	34	34	34	34	31	35	65	-8
61	61	61	61	61	61	61	61	62	62	49	63	86	-11
52	52	52	52	52	52	52	52	62	52	48	53	90	-22
62	62	62	62	62	62	62	62	62	62	48	63	91	-25
62	62	62	62	62	62	62	61	62	62	48	53	91	-26
62	62	62	61	61	61	61	61	62	62	48	53	91	-26
61	61	61	61	61	61	61	61	62	62	48	63	91	-26
61	61	61	61	61	61	61	61	62	62	48	63	91	-24
61	61	61	61	61	61	61	61	62	62	48	63	91	-26
61	61	61	61	61	61	61	61	62	52	48	63	91	-26
61	61	61	61	61	61	61	61	62	62	48	63	91	-26
61	61	61	61	61	61	61	61	62	62	48	63	91	-25
61	61	61	61	61	61	61	61	62	62	48	63	91	-26
61	61	61	61	61	61	61	61	52	52	48	53	91	-25
61	61	61	61	61	61	61	61	62	62	48	63	91	-26

SPEC 5.1 BOTTOM HALF OF CYLINDER THERMO LOADS

0 23 SCALE

3 BLK
12 OF 21

1/1/1

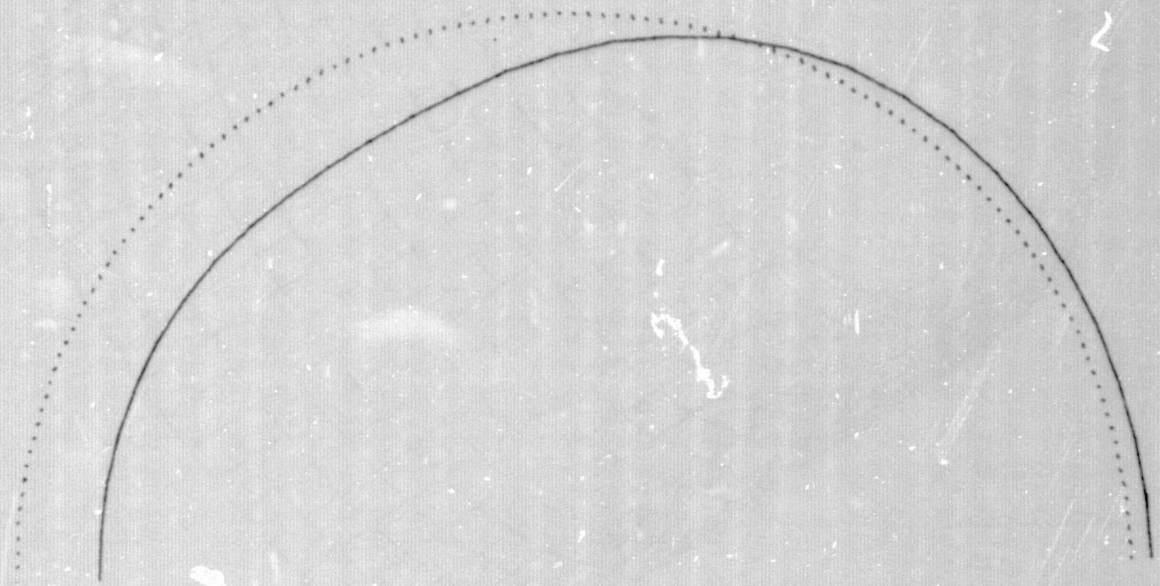


0 42
SCALE

3 BLK
13 OF 21

SPEC ALL

1/1/1



SPEC 2.1 RING

0 35 SCALE

3 BLK
14 OF 21

1/1/1

DISPLAY= SX /1000 . NODE= 4 . SURFACE= 2

0	0	0	0	0	0	0	0	0	0	0	2	-5	-11
0	0	0	0	0	0	0	0	0	0	0	2	-5	-11
0	0	0	0	0	0	0	0	0	0	0	2	-5	-11
0	0	0	0	0	0	0	0	0	0	0	2	-5	-11
0	0	0	0	0	0	0	0	0	0	0	2	-5	-11
0	0	0	0	0	0	0	0	0	0	0	2	-5	-11
0	0	0	0	0	0	0	0	0	0	0	2	-5	-11
0	0	0	0	0	0	0	0	0	0	0	2	-5	-11
-1	-1	0	0	0	0	0	0	0	0	0	2	-5	-10
-1	-1	-1	-1	-1	-1	-1	-1	0	-1	0	1	-5	-10
-1	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1	1	-5	-9
-1	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1	0	-6	-7
-1	-1	-1	-1	-1	-1	-1	-1	-1	-1	-2	0	-6	-2
0	0	0	0	0	-1	-1	-1	-1	-1	-2	-1	-4	6
0	0	0	0	0	0	0	0	0	0	-1	-1	0	24

SPEC 4.1

TOP HALF OF CYLINDER
THERMO LOADS

0 SCALE 23

3 BLK
15 OF 21

1/1/1

DISPLAY= SY /1000 , NODE= 4. SURFACE= 1

-13	-13	-13	-13	-13	-13	-13	-13	-13	-13	-14	-12	-3	-32
-13	-13	-13	-13	-13	-13	-13	-13	-13	-13	-14	-12	-3	-32
-13	-13	-13	-13	-13	-13	-13	-13	-13	-13	-14	-12	-3	-32
-13	-13	-13	-13	-13	-13	-13	-13	-13	-13	-14	-12	-3	-32
-13	-13	-13	-13	-13	-13	-13	-13	-13	-13	-14	-12	-3	-32
-13	-13	-13	-13	-13	-13	-13	-13	-13	-13	-14	-13	-3	-32
-13	-13	-13	-13	-13	-13	-13	-13	-13	-13	-14	-13	-3	-32
-13	-13	-13	-13	-13	-13	-13	-13	-13	-13	-14	-12	-3	-32
-12	-12	-12	-12	-12	-12	-12	-13	-12	-12	-14	-12	-3	-32
-12	-12	-12	-12	-12	-12	-12	-12	-12	-12	-13	-12	-3	-31
-12	-12	-12	-12	-12	-12	-12	-12	-12	-12	-12	-11	-3	-29
-11	-11	-11	-11	-11	-11	-11	-11	-11	-10	-11	-10	-2	-26
-9	-9	-9	-9	-8	-8	-8	-8	-8	-8	-8	-8	-2	-18
-3	-3	-3	-3	-3	-3	-3	-3	-3	-3	-3	-4	-2	-1
8	8	8	8	8	8	8	8	8	8	9	6	0	30

SPEC, 4.1 TOP HALF OF CYLINDER
THERMO LOADS

0 SCALE 23

3 BLK
16 OF 21

DISPLAY= SX /1000 . NODE= 4[illegible] SURFACE= 1

0	0	C	0	0	0	0	0	0	0	0	2	1	-22
0	0	0	0	0	0	0	0	0	0	0	2	1	-22
0	0	0	0	0	0	0	0	0	0	0	2	1	-22
0	0	0	0	0	0	0	0	0	0	0	2	1	-22
0	0	0	0	0	0	0	0	0	0	0	2	1	-22
0	0	0	0	0	0	0	0	0	0	0	2	1	-22
0	0	0	0	0	0	0	0	0	0	0	2	1	-22
0	0	0	0	0	0	0	0	0	0	0	2	1	-22
1	0	0	0	0	0	0	0	0	[illegible]	0	2	1	-22
1	1	1	1	1	1	1	1	1	0	0	2	1	-21
1	1	1	1	1	1	1	1	1	1	0	2	2	-20
1	1	1	1	1	1	1	1	1	1	1	2	3	-18
1	1	1	1	1	1	1	1	1	1	2	1	6	-13
0	0	0	0	0	0	1	1	1	1	2	-2	8	0
0	C	0	0	0	0	0	0	0	1	1	-6	7	29

SPEC
4.1

TOP HALF OF CYLINDER
THERMO LOADS

0 ———— 23
SCALE

3 BLK
17 OF 21

DISPLAY= SX /1000 . NODE= 4. SURFACE= 0

0	0	0	0	0	0	0	0	0	0	0	-5	4	64
0	0	0	0	0	0	0	0	0	1	0	-6	6	66
0	0	0	0	0	0	0	0	0	1	0	-7	8	66
0	0	0	0	0	0	0	0	0	1	0	-7	8	66
0	0	0	0	0	0	0	0	0	1	0	-7	8	66
0	0	0	0	0	0	0	0	0	1	0	-7	8	66
0	0	0	0	0	0	0	0	0	1	0	-7	8	66
0	0	0	0	0	0	0	0	0	1	0	-7	8	66
0	0	0	0	0	0	0	0	0	1	0	-7	8	66
0	0	0	0	0	0	0	0	0	1	0	-7	8	66
0	0	0	0	0	0	0	0	0	1	0	-7	8	66
0	0	0	0	0	0	0	0	0	1	0	-7	8	66
0	0	0	0	0	0	0	0	0	1	0	-7	8	66
0	0	0	0	0	0	0	0	0	1	0	-7	8	66
0	0	0	0	0	0	0	0	0	1	0	-7	8	66

SPEC 5.1 BOTTOM HALF OF CYLINDER
THERMO LOADS

0 23
SCALE

3 BLK
18 OF 21

1/1/1

DISPLAY= SX /1000 . NODE= 7. SURFACE= 1

0	0	0	0	0	0	0	0	-1	0	0	-8	1	64
0	0	0	-1	-1	-1	-1	-1	-1	-1	0	-10	-4	83
-1	-1	-1	-1	-1	-1	-1	-1	-1	-1	0	-10	-5	87
-1	-1	-1	-1	-1	-1	-1	-1	-1	-1	0	-9	-5	88
-1	-1	-1	-1	-1	-1	-1	-1	-1	0	1	-8	-4	89
-1	-1	-1	-1	-1	-1	-1	0	-1	0	1	-7	-4	89
0	0	0	0	0	0	0	0	0	0	1	-7	-4	89
0	0	0	0	0	0	0	0	0	0	1	-7	-4	89
0	0	0	0	0	0	0	0	0	1	1	-7	-4	89
0	0	0	0	0	0	0	0	0	0	1	-7	-4	89
0	0	0	0	0	0	0	0	0	0	1	-7	-4	89
0	0	0	0	0	0	0	0	0	0	1	-7	-4	89
0	0	0	0	0	0	0	0	0	0	1	-7	-4	89
0	0	0	0	0	0	0	0	0	0	1	-7	-4	89
0	0	0	0	0	0	0	0	0	0	1	-7	-4	89

SPEC 5.1 BOTTOM HALF OF CYLINDER
THERMO LOADS

0 23
SCALE

3 BLK
19 OF 21

DISPLAY= SX /1000 . NODE= 4. SURFACE= 0

0	0	0	0	0	0	0	0	0	0	0	2	-2	-16
0	0	0	0	0	0	0	0	0	0	0	2	-2	-16
0	0	0	0	0	0	0	0	0	0	0	2	-2	-16
0	0	0	0	0	0	0	0	0	0	0	2	-2	-16
0	0	0	0	0	0	0	0	0	0	0	2	-2	-16
0	0	0	0	0	0	0	0	0	0	0	2	-2	-16
0	0	0	0	0	0	0	0	0	0	0	2	-2	-16
0	0	0	0	0	0	0	0	0	0	0	2	-2	-16
0	0	0	0	0	0	0	0	0	0	0	2	-2	-16
0	0	0	0	0	0	0	0	0	0	0	2	-2	-16
0	0	0	0	0	0	0	0	0	0	0	1	-2	-15
0	0	0	0	0	0	0	0	0	0	0	1	-1	-12
0	0	0	0	0	0	0	0	0	0	0	0	0	-8
0	0	0	0	0	0	0	0	0	0	0	-1	2	3
0	0	0	0	0	0	0	0	0	0	0	-3	4	27

SPEC 4.1

TOP HALF OF CYLINDER
THERMO LOADS

0 23
SCALE

3 BLK
20 of 21

1 / 1 / 1

DISPLAY= SY /1000 , NODE= 4 SURFACE= 2

-13	-13	-13	-13	-13	-13	-13	-13	-13	-13	-12	-13	-23	6
-13	-13	-13	-13	-13	-13	-13	-13	-13	-13	-12	-13	-23	6
-13	-13	-13	-13	-13	-13	-13	-13	-13	-13	-12	-13	-23	6
-13	-13	-13	-13	-13	-13	-13	-13	-13	-13	-12	-13	-23	6
-13	-13	-13	-13	-13	-13	-13	-13	-13	-13	-12	-13	-23	6
-13	-13	-13	-13	-13	-13	-13	-13	-13	-13	-12	-13	-23	6
-13	-13	-13	-13	-13	-13	-13	-13	-13	-13	-12	-13	-23	6
-13	-13	-13	-13	-13	-13	-13	-13	-13	-13	-12	-13	-23	6
-13	-13	-13	-13	-13	-13	-13	-13	-13	-13	-12	-13	-22	6
-13	-13	-13	-13	-13	-13	-13	-13	-13	-13	-12	-13	-22	6
-12	-12	-12	-12	-12	-12	-12	-12	-12	-12	-11	-12	-21	6
-11	-11	-11	-11	-11	-11	-11	-11	-11	-11	-11	-11	-19	6
-9	-9	-9	-9	-9	-9	-9	-9	-9	-9	-9	-9	-16	3
-4	-4	-4	-4	-4	-4	-4	-4	-4	-4	-4	-3	-5	-2
8	8	8	8	8	8	8	8	8	8	7	9	16	-9

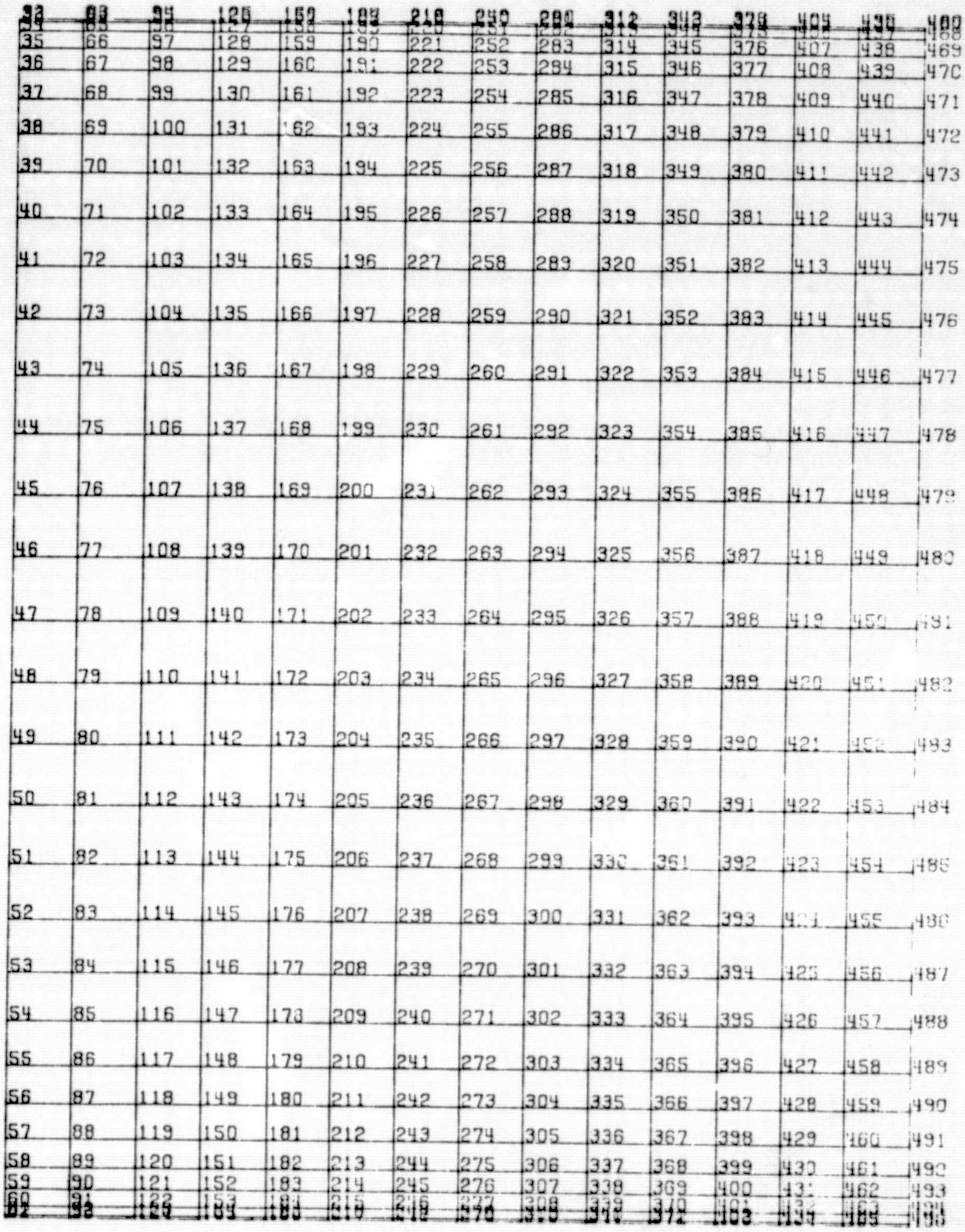
SPEC 4.1

TOP HALF OF CYLINDER
THERMO LOADS

0 ——— 23
SCALE

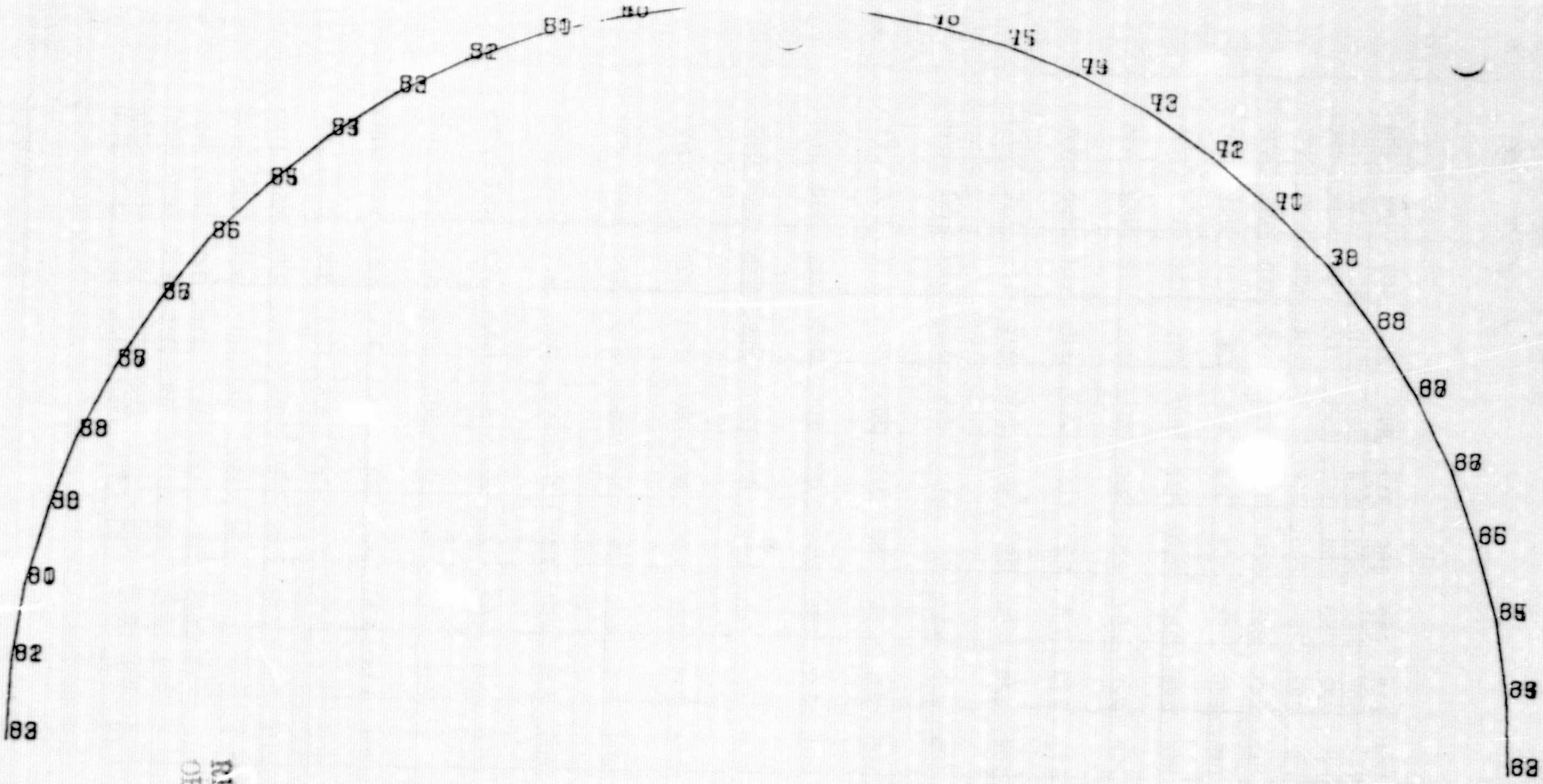
3 BLK
21 OF 21

15 BLK
- RUN "ECK"
1 OF 18



SHELL AND RING ....ALL....

SCALE



PEC RING
.1

0 30
SCALE

15 BLK
2 of 18

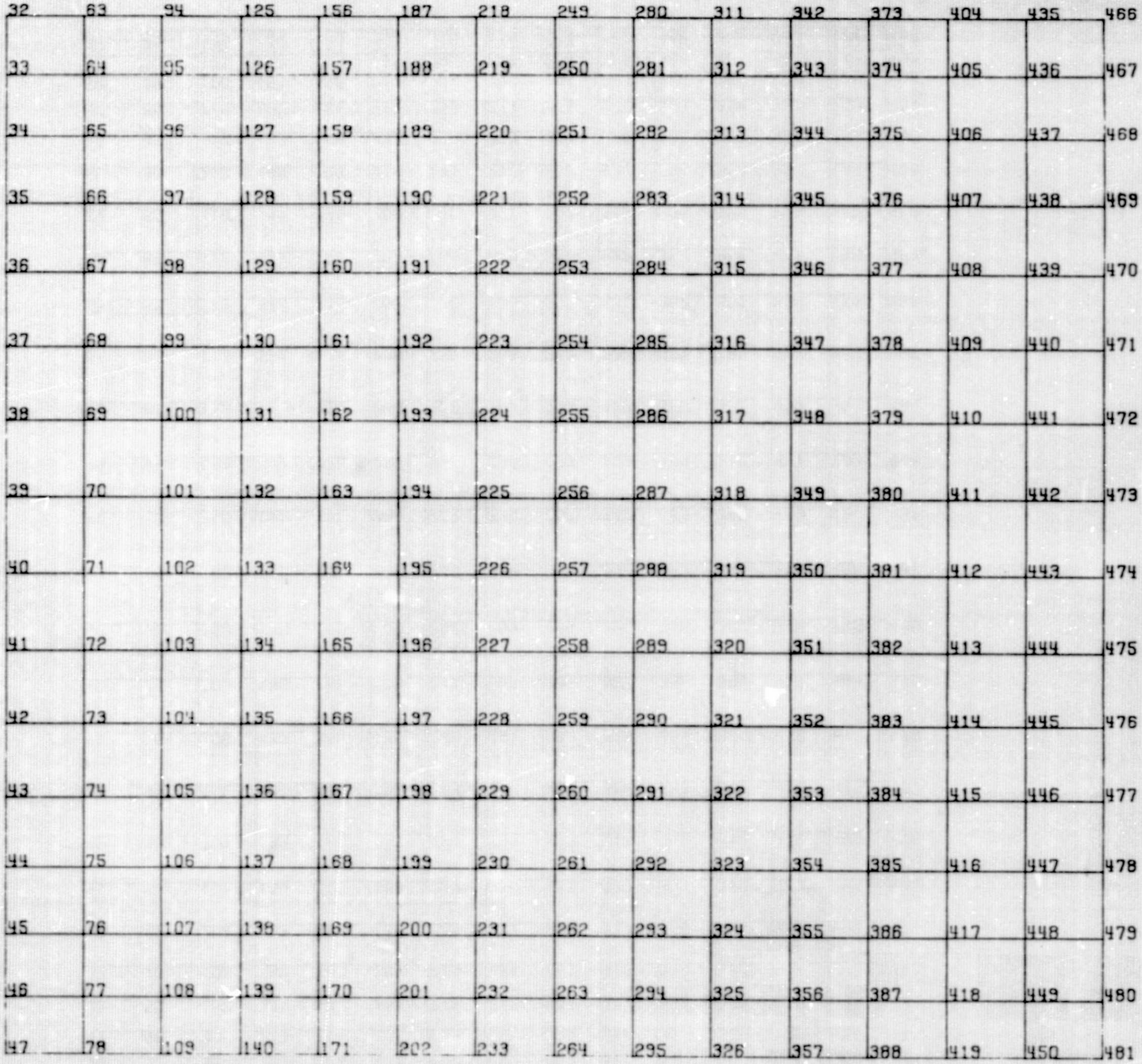
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
35	66	97	128	159	190	221	252	283	314	345	376	407	438	469
36	67	98	129	160	191	222	253	284	315	346	377	408	439	470
37	68	99	130	161	192	223	254	285	316	347	378	409	440	471
38	69	100	131	162	193	224	255	286	317	348	379	410	441	472
39	70	101	132	163	194	225	256	287	318	349	380	411	442	473
40	71	102	133	164	195	226	257	288	319	350	381	412	443	474
41	72	103	134	165	196	227	258	289	320	351	382	413	444	475
42	73	104	135	166	197	228	259	290	321	352	383	414	445	476
43	74	105	136	167	198	229	260	291	322	353	384	415	446	477
44	75	106	137	168	199	230	261	292	323	354	385	416	447	478
45	76	107	138	169	200	231	262	293	324	355	386	417	448	479
46	77	108	139	170	201	232	263	294	325	356	387	418	449	480
47	78	109	140	171	202	233	264	295	326	357	388	419	450	481
48	79	110	141	172	203	234	265	296	327	358	389	420	451	482
49	80	111	142	173	204	235	266	297	328	359	390	421	452	483
50	81	112	143	174	205	236	267	298	329	360	391	422	453	484
51	82	113	144	175	206	237	268	299	330	361	392	423	454	485
52	83	114	145	176	207	238	269	300	331	362	393	424	455	486
53	84	115	146	177	208	239	270	301	332	363	394	425	456	487
54	85	116	147	178	209	240	271	302	333	364	395	426	457	488
55	86	117	148	179	210	241	272	303	334	365	396	427	458	489
56	87	118	149	180	211	242	273	304	335	366	397	428	459	490
57	88	119	150	181	212	243	274	305	336	367	398	429	460	491
58	89	120	151	182	213	244	275	306	337	368	399	430	461	492
59	90	121	152	183	214	245	276	307	338	369	400	431	462	493
60	91	122	153	184	215	246	277	308	339	370	401	432	463	494
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]

SPEC 3.1

SHELL

0 30
SCALE

15 BLK
3 OF 18



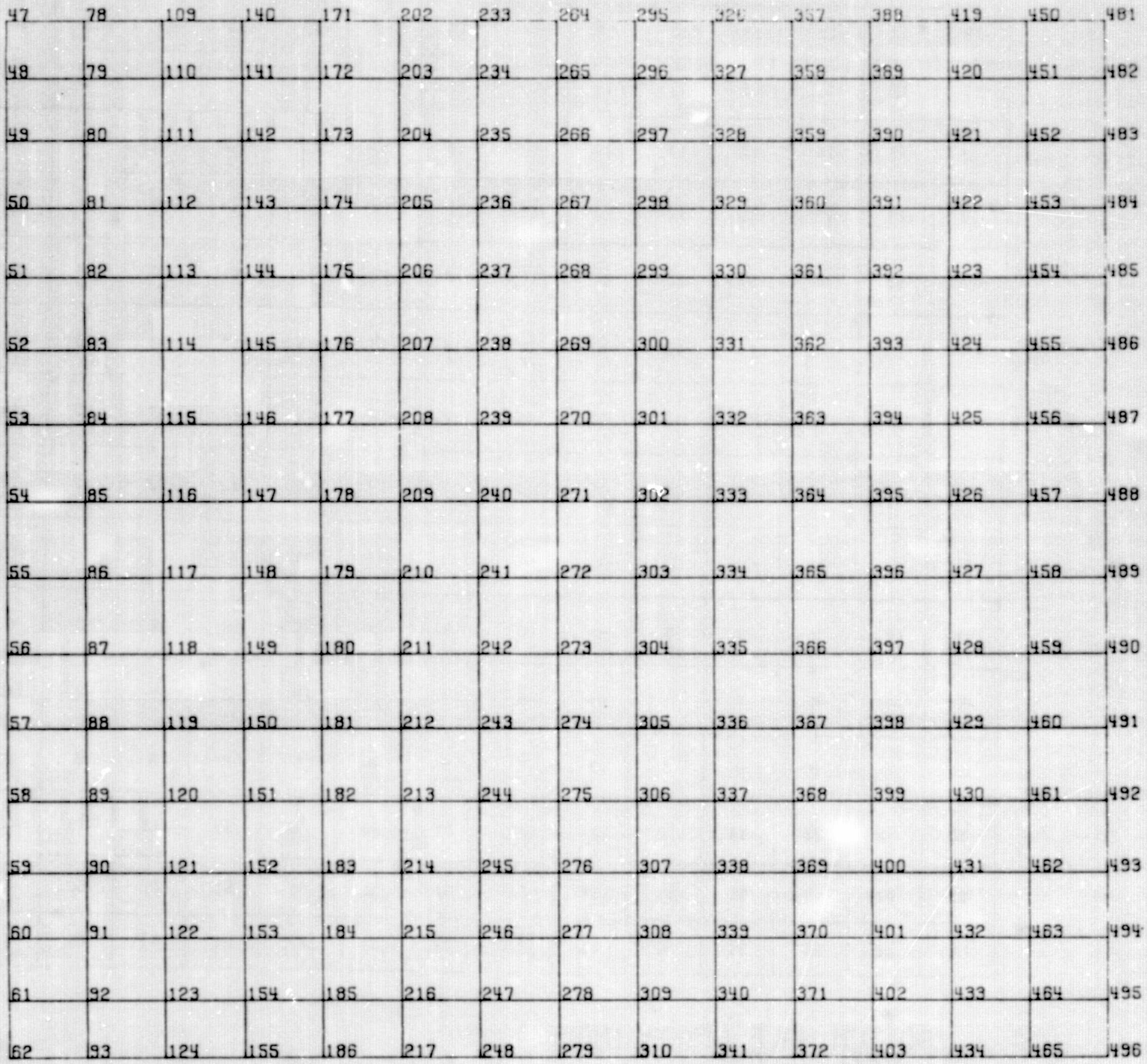
SPEC
4.1

TOP HALF OF CYLINDER
THERMO LOADS

0 .23
SCALE

15 BLK
4 OF 18

15 BLK
5 OF 18



SPEC · BOTTOM HALF OF CYLINDER 0 23

DISPLAY= SY /1000 , NODE 4 , SURFACE C

-13	-13	-13	-13	-13	-13	-13	-13	-13	-13	-13	-13	-13	-13
-13	-13	-13	-13	-13	-13	-13	-13	-13	-13	-13	-13	-13	-13
-13	-13	-13	-13	-13	-13	-13	-13	-13	-13	-13	-13	-13	-13
-13	-13	-13	-13	-13	-13	-13	-13	-13	-13	-13	-13	-13	-13
-13	-13	-13	-13	-13	-13	-13	-13	-13	-13	-13	-13	-13	-13
-13	-13	-13	-13	-13	-13	-13	-13	-13	-13	-13	-13	-13	-13
-12	-12	-12	-12	-12	-12	-12	-12	-12	-12	-12	-12	-13	-13
-12	-12	-12	-12	-12	-12	-12	-12	-12	-12	-12	-12	-12	-12
-11	-11	-11	-11	-11	-11	-11	-11	-11	-11	-11	-11	-11	-10
-9	-9	-9	-9	-9	-9	-9	-9	-9	-9	-8	-8	-8	-7
-4	-4	-4	-4	-4	-4	-4	-4	-3	-3	-3	-4	-4	-2
8	8	8	8	8	8	8	8	8	8	8	8	8	11
33	33	33	33	33	33	33	33	33	33	33	33	34	35
51	51	51	51	51	51	51	51	51	51	51	51	52	51
52	52	51	51	51	51	51	51	51	51	51	51	51	51

3-BLK CASE
RUN DF=

6 OF 18

15 BLK

SPEC 5.1 BOTTOM HALF OF CYLINDER
THERMO LOADS

0 23
SCALE

DISPLAY= SY /1000 , NODE= 4, SURFACE= 1

-13	-13	-13	-13	-13	-13	-13	-13	-13	-13	-14	-12	-3	-32
-13	-13	-13	-13	-13	-13	-13	-13	-13	-13	-14	-12	-3	-32
-13	-13	-13	-13	-13	-13	-13	-13	-13	-13	-14	-13	-3	-32
-13	-13	-13	-13	-13	-13	-13	-13	-13	-13	-14	-13	-3	-32
-13	-13	-13	-13	-13	-13	-13	-13	-13	-13	-14	-13	-3	-32
-12	-12	-12	-12	-12	-12	-12	-13	-12	-13	-14	-12	-3	-32
-12	-12	-12	-12	-12	-12	-12	-12	-12	-12	-13	-12	-3	-31
-12	-12	-12	-12	-12	-12	-12	-12	-12	-12	-12	-11	-3	-29
-11	-11	-11	-11	-11	-11	-11	-11	-11	-10	-11	-10	-2	-26
-9	-9	-9	-9	-8	-8	-8	-8	-8	-8	-8	-8	-2	-18
-4	-3	-3	-3	-3	-3	-3	-3	-3	-3	-3	-4	-2	-1
8	8	8	8	8	8	8	8	8	8	9	6	0	30
33	33	33	33	33	33	33	33	33	33	35	31	12	78
51	51	51	51	51	51	51	51	50	50	54	49	18	114
51	51	51	51	51	51	51	51	50	50	54	49	13	124

SPEC 5.1

BOTTOM HALF OF CYLINDER
THERMO LOADS

0 23
SCALE

15 BLK
7 OF 18

DISPLAY= SY /1CCC , NODE= 4, SURFACE= 2

-13	-13	-13	-13	-13	-13	-13	-13	-13	-13	-12	-13	-23	6
-13	-13	-13	-13	-13	-13	-13	-13	-13	-13	-12	-13	-23	6
-13	-13	-13	-13	-13	-13	-13	-13	-13	-13	-12	-13	-23	6
-13	-13	-13	-13	-13	-13	-13	-13	-13	-13	-12	-13	-23	6
-13	-13	-13	-13	-13	-13	-13	-13	-13	-13	-12	-13	-23	6
-13	-13	-13	-13	-13	-13	-13	-13	-13	-13	-12	-13	-23	6
-13	-13	-13	-13	-13	-13	-13	-13	-13	-13	-12	-13	-22	6
-12	-12	-12	-12	-12	-12	-12	-12	-12	-12	-11	-12	-21	6
-11	-11	-11	-11	-11	-11	-11	-11	-11	-11	-11	-11	-19	5
-9	-9	-9	-9	-9	-9	-9	-9	-9	-9	-9	-9	-15	3
-4	-4	-4	-4	-4	-4	-4	-4	-4	-4	-4	-3	-5	-2
8	8	8	8	8	8	8	8	8	8	7	10	16	-9
34	34	34	34	34	34	34	34	34	34	31	35	56	-8
51	51	51	51	51	51	51	51	52	52	49	53	85	-12
52	52	52	52	52	52	52	52	52	52	48	53	90	-22

SPEC 5.1 BOTTOM HALF OF CYLINDER
THERMO LOADS

0 SCALE 23

15 BLK
8 OF 18

1/1/1

DISPLAY= SY /1000 , NODE= - 9 , SURFACE= 0

-13	-13	-13	-13	-13	-13	-13	-13	-13	-13	-13	-13	-13	-13
-13	-13	-13	-13	-13	-13	-13	-13	-13	-13	-13	-13	-13	-13
-13	-13	-13	-13	-13	-13	-13	-13	-13	-13	-13	-13	-13	-13
-13	-13	-13	-13	-13	-13	-13	-13	-13	-13	-13	-13	-13	-13
-13	-13	-13	-13	-13	-13	-13	-13	-13	-13	-13	-13	-13	-13
-13	-13	-13	-13	-13	-13	-13	-13	-13	-13	-13	-13	-13	-13
-13	-13	-13	-13	-13	-13	-13	-13	-13	-13	-13	-13	-13	-13
-13	-13	-13	-13	-13	-13	-13	-13	-13	-13	-13	-13	-13	-13
-13	-13	-13	-13	-13	-13	-13	-13	-13	-13	-13	-13	-13	-13
-13	-13	-13	-13	-13	-13	-13	-13	-13	-13	-13	-13	-13	-13
-13	-13	-13	-13	-13	-13	-13	-13	-13	-13	-13	-13	-13	-13
-13	-13	-13	-13	-13	-13	-13	-13	-13	-13	-13	-13	-13	-13
-13	-13	-13	-13	-13	-13	-13	-13	-13	-13	-13	-13	-13	-13
-13	-13	-13	-13	-13	-13	-13	-13	-13	-13	-13	-13	-13	-13
-13	-13	-13	-13	-13	-13	-13	-13	-13	-13	-13	-13	-13	-13

SPEC 4.1

TOP HALF OF CYLINDER
THERMO LOADS

0 23
SCALE

15 BLK
9 OF 18

DISPLAY= SY /1000 , NODE= -1 , SURFACE= 1

-13	-13	-13	-13	-13	-13	-13	-13	-13	-13	-14	-12	-3	-32
-13	-13	-13	-13	-13	-13	-13	-13	-13	-13	-14	-12	-3	-32
-13	-13	-13	-13	-13	-13	-13	-13	-13	-13	-14	-12	-3	-32
-13	-13	-13	-13	-13	-13	-13	-13	-13	-13	-14	-12	-3	-32
-13	-13	-13	-13	-13	-13	-13	-13	-13	-13	-14	-12	-3	-32
-13	-13	-13	-13	-13	-13	-13	-13	-13	-13	-14	-12	-3	-32
-13	-13	-13	-13	-13	-13	-13	-13	-13	-13	-14	-12	-3	-32
-13	-13	-13	-13	-13	-13	-13	-13	-13	-13	-14	-12	-3	-32
-13	-13	-13	-13	-13	-13	-13	-13	-13	-13	-14	-12	-3	-32
-13	-13	-13	-13	-13	-13	-13	-13	-13	-13	-14	-12	-3	-32
-13	-13	-13	-13	-13	-13	-13	-13	-13	-13	-14	-12	-3	-32
-13	-13	-13	-13	-13	-13	-13	-13	-13	-13	-14	-12	-3	-32
-13	-13	-13	-13	-13	-13	-13	-13	-13	-13	-14	-12	-3	-32
-13	-13	-13	-13	-13	-13	-13	-13	-13	-13	-14	-12	-3	-32
-13	-13	-13	-13	-13	-13	-13	-13	-13	-13	-14	-12	-3	-32

SPEC 4.1 TOP HALF OF CYLINDER
THERMO LOADS

0 ——— 23
SCALE

15 BLK
10 OF 10

DISPLAY= SY /1000 , NODE= 4, SURFACE= 2

-13	-13	-13	-13	-13	-13	-13	-13	-13	-13	-12	-13	-23	6
-13	-13	-13	-13	-13	-13	-13	-13	-13	-13	-12	-13	-23	6
-13	-13	-13	-13	-13	-13	-13	-13	-13	-13	-12	-13	-23	6
-13	-13	-13	-13	-13	-13	-13	-13	-13	-13	-12	-13	-23	6
-13	-13	-13	-13	-13	-13	-13	-13	-13	-13	-12	-13	-23	6
-13	-13	-13	-13	-13	-13	-13	-13	-13	-13	-12	-13	-23	6
-13	-13	-13	-13	-13	-13	-13	-13	-13	-13	-12	-13	-23	6
-13	-13	-13	-13	-13	-13	-13	-13	-13	-13	-12	-13	-23	6
-13	-13	-13	-13	-13	-13	-13	-13	-13	-13	-12	-13	-23	6
-13	-13	-13	-13	-13	-13	-13	-13	-13	-13	-12	-13	-23	6
-13	-13	-13	-13	-13	-13	-13	-13	-13	-13	-12	-13	-23	6
-13	-13	-13	-13	-13	-13	-13	-13	-13	-13	-12	-13	-23	6
-13	-13	-13	-13	-13	-13	-13	-13	-13	-13	-12	-13	-23	6
-13	-13	-13	-13	-13	-13	-13	-13	-13	-13	-12	-13	-23	6
-13	-13	-13	-13	-13	-13	-13	-13	-13	-13	-12	-13	-23	6

SPEC
4.1

TOP HALF OF CYLINDER
THERMO LOADS

0 23
SCALE

15 BLK
11 OF 18

DISPLAY= SX /1000 , NODE= 4, SURFACE= 1 1/1/1

0	0	0	0	0	0	0	0	0	0	0	2	1	-22
0	0	0	0	0	0	0	0	0	0	0	2	1	-22
0	0	0	0	0	0	0	0	0	0	0	2	1	-22
0	0	0	0	0	0	0	0	0	0	0	2	1	-22
0	0	0	0	0	0	0	0	0	0	0	2	1	-22
0	0	0	0	0	0	0	0	0	0	0	2	1	-22
0	0	0	0	0	0	0	0	0	0	0	2	1	-22
0	0	0	0	0	0	0	0	0	0	0	2	1	-22
0	0	0	0	0	0	0	0	0	0	0	2	1	-22
0	0	0	0	0	0	0	0	0	0	0	2	1	-22
0	0	0	0	0	0	0	0	0	0	0	2	1	-22
0	0	0	0	0	0	0	0	0	0	0	2	1	-22
0	0	0	0	0	0	0	0	0	0	0	2	1	-22
0	0	0	0	0	0	0	0	0	0	0	2	1	-22
0	0	0	0	0	0	0	0	0	0	0	2	1	-22

15 BLK
12 OF 18

SPEC 4.1

TOP HALF OF CYLINDER
THERMO LOADS

0 23
SCALE

1/1/1

DISPLAY= SX /1000 , NODE= 4, SURFACE= 0

0	0	0	0	0	0	0	0	0	0	0	2	-2	-16
0	0	0	0	0	0	0	0	0	0	0	2	-2	-16
0	0	0	0	0	0	0	0	0	0	0	2	-2	-16
0	0	0	0	0	0	0	0	0	0	0	2	-2	-16
0	0	0	0	0	0	0	0	0	0	0	2	-2	-16
0	0	0	0	0	0	0	0	0	0	0	2	-2	-16
0	0	0	0	0	0	0	0	0	0	0	2	-2	-16
0	0	0	0	0	0	0	0	0	0	0	2	-2	-16
0	0	0	0	0	0	0	0	0	0	0	2	-2	-16
0	0	0	0	0	0	0	0	0	0	0	2	-2	-16
0	0	0	0	0	0	0	0	0	0	0	2	-2	-16
0	0	0	0	0	0	0	0	0	0	0	2	-2	-16
0	0	0	0	0	0	0	0	0	0	0	2	-2	-16
0	0	0	0	0	0	0	0	0	0	0	2	-2	-16
0	0	0	0	0	0	0	0	0	0	0	2	-2	-16

15 BLK
13 OF 18

SPEC TOP HALF OF CYLINDER

DISPLAY= SX /1000 , NODE= 4. SURFACE= 1 1/1/1

0	0	0	0	0	0	0	0	0	0	0	2	1	-22
0	0	0	0	0	0	0	0	0	0	0	2	1	-22
0	0	0	0	0	0	0	0	0	0	0	2	1	-22
0	0	0	0	0	0	0	0	0	0	0	2	1	-22
0	0	0	0	0	0	0	0	0	0	0	2	1	-22
1	1	1	0	0	0	0	0	0	0	0	2	1	-22
1	1	1	1	1	1	1	1	1	0	0	2	1	-21
1	1	1	1	1	1	1	1	1	1	0	2	2	-20
1	1	1	1	1	1	1	1	1	1	1	2	3	-18
1	1	1	1	1	1	1	1	1	1	2	1	5	-13
0	0	0	0	0	1	1	1	1	1	2	-2	8	0
0	0	0	0	0	0	0	0	0	1	1	-5	7	29
-1	-1	-1	-1	-1	-1	-1	-1	-1	0	0	-8	1	64
-1	-1	-1	-1	-1	-1	-1	-1	-1	-1	0	-10	-4	83
-1	-1	-1	-2	-2	-2	-2	-2	-2	-2	-1	-10	-5	[illegible]

SPEC 5.1 BOTTOM HALF OF CYLINDER
THERMO LOADS

0 23
SCALE

15 BLK
14 OF 18

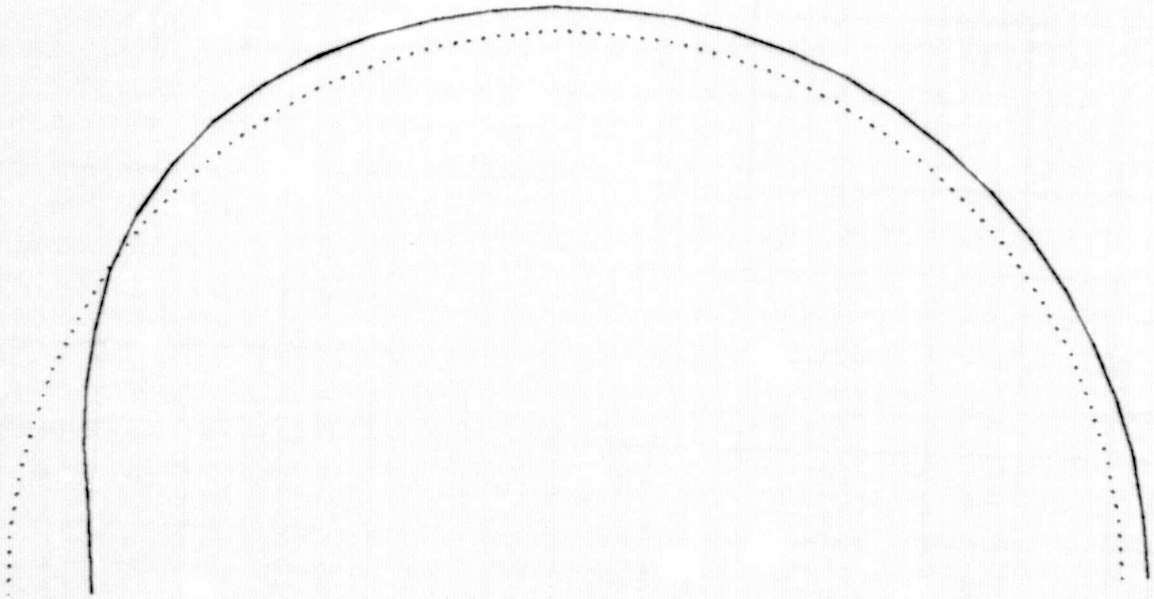
DISPLAY= SX /1000 , NODE= , SURFACE= 2

0	0	0	0	0	0	0	0	0	0	0	2	-5	-11
0	0	0	0	0	0	0	0	0	0	0	2	-5	-11
0	0	0	0	0	0	0	0	0	0	0	2	-5	-11
0	0	0	0	0	0	0	0	0	0	0	2	-5	-11
0	0	0	0	0	0	0	0	0	0	0	2	-5	-11
-1	-1	-1	0	0	0	0	0	0	0	0	2	-5	-10
-1	-1	-1	-1	-1	-1	-1	-1	0	-1	0	1	-5	-10
-1	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1	1	-5	-9
-1	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1	0	-6	-7
-1	-1	-1	-1	-1	-1	-1	-1	-1	-1	-2	0	-6	-2
0	0	0	0	-1	-1	-1	-1	-1	-1	-2	-1	-4	6
0	0	0	0	0	0	0	0	0	0	-1	-1	0	25
1	1	1	1	1	1	1	1	1	1	0	-1	8	45
1	1	1	1	1	1	1	1	1	2	1	-2	16	49
1	1	2	2	2	2	2	2	2	3	1	-3	20	44

SPEC 5.1 BOTTOM HALF OF CYLINDER THERMO LOADS

0 23 SCALE

15 BLK
15 OF 13

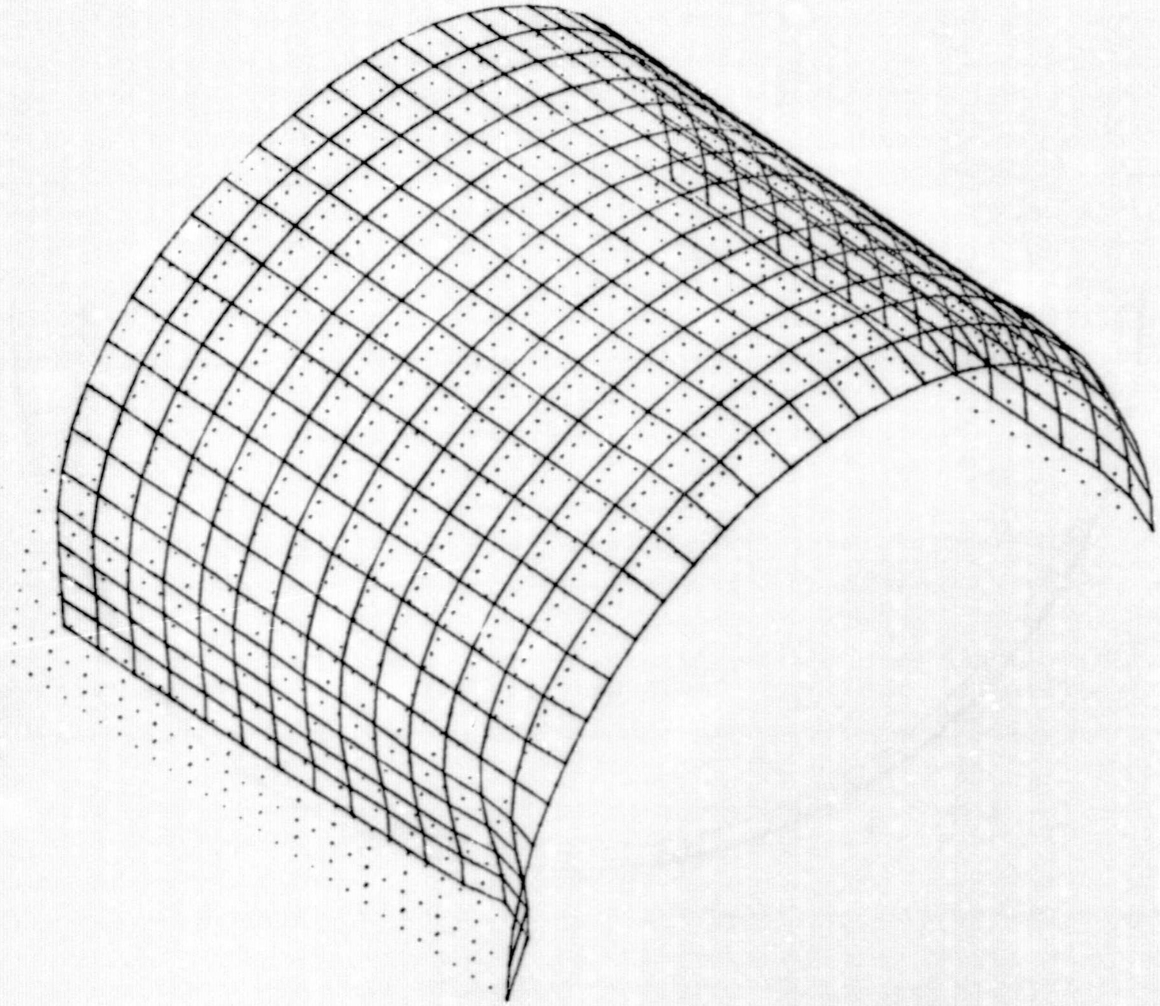


SPEC
2.1

RING

0 35
SCALE

15 BLR
16 of 18

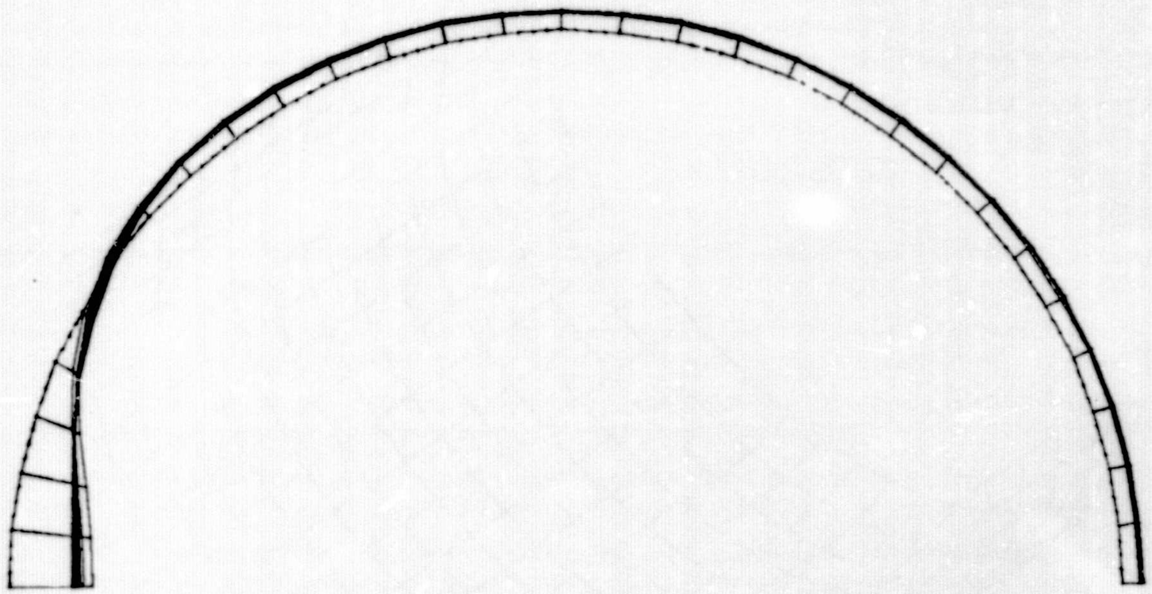


SPEC
6.1

ALL

0 SCALE 42

15 BLK
17 OF 18



SPEC
7.1

ALL

0 35
SCALE

15 BLK
18 OF 18

FATIGUE DAMAGE FROM LN2 OR GN2 AT DIFF LOCATIONS IN TUNNEL

1. TYPICAL STRUCT RING

Stress Values

	Pressure	Transient Thermal	LN2 ACCIDENT THERMAL STRESSES small accid.	large accid.
σ_H	17	6.5	—	—
σ_L	25	-16.0	60, & -2.8	31. & -32.

operating cycle - NORMAL

	cd+P	P	Htup+P	End
σ_H	23.5	17	10.5	0
σ_L	9	25	41	0

$= \Delta S = 41$

operating cycle with accident during S.S.
small accident

σ_H	23.5	17	10.5	0
σ_L	68.0	85.	41 *	0

$\Rightarrow \Delta S = 85$

operating cycle with accident begining Trans Cd
large accident

σ_H	23.5	17	10.5	0
σ_L	-23	-7	9	0

$\Delta S = 46.5$

REPRODUCIBILITY OF THE ORIGINAL PAGE IS POOR

∴ Small accident yields higher stresses

* Accident stresses do not add to ht up cycle because circumferential grad. will be [illegible] during heat up.

BY______ DATE______ SUBJECT______ SHEET NO.______ OF______
CHKD. BY______ DATE______ JOB NO.______

$$S_A = \frac{1}{2}(85)(3) = 127.5 \Rightarrow N = 300 \text{ cycles}$$

from ASME CODE

This is stress level during accident and the fatigue damage from this accident must be added to the fatigue damage from normal operation to determine how it affects shell life.

Life of vessel for normal operation (L) = 31 years

Damage factor for normal operation $\equiv \sum_{i=1}^{n} \frac{n_i}{N_i}$

$$20\left(\frac{1}{\sum \frac{n_i}{N_i}}\right) = L \quad \text{or} \quad \sum \frac{n_i}{N_i} = \frac{20}{L}$$

$$\therefore \sum \frac{n_i}{N_i} = \frac{20}{31} = .645$$

$N_a \equiv$ # of accidents

Total fatigue damage ≤ 1 in 20 years

$$\sum \frac{n_i}{N_i} + \frac{N_a}{N} \leq 1$$

$$\text{or} \quad L = \frac{20}{\sum \frac{n_i}{N_i} + \frac{N_a}{N}}$$

N_a	L years
1	31
10	29
50	25
100	21

BY	DATE	SUBJECT	SHEET NO.	OF
CHKD. BY	DATE		JOB NO.	

2. ELLIPTICAL RING-WELD

Stress Values

		Press	therm	LN2 Accident Thermal Stress small	Large
σ_H	I	22.22	6.5	-1.	
	O	12.57	22.0		
σ_L	I	20.63	-16.0	60. & -2.8	31. & -32.0
	O	-11.22	16.0		

worst stresses will occur during small accident on inside

	cd+P	P	Ht+P	End
σ_H	28.77	22.22	15.72	0
σ_L	64.63	80.63	36.63	0

$\Delta S = 80.63$

$S_A = \frac{1}{2}(80.63)(3) = 121 \Rightarrow N = 300$

For normal operation $L = 15$ years

Na	L
1	15
10	15
50	14
100	12

$\Rightarrow$ from linear regression Anal.
$\Delta L = .03\, Na$

-.0309
15.24
.22

REF: 1 NASA-CR-115301
ENGINEERING HANDBOOK FOR THERMOSTRUCTURAL ANALYSIS OF PLATES & SHELLS.

THERMAL BUCKLING OF ISOTROPIC CIRCULAR CYLINDRICAL SHELLS; EITHER EDGE CLAMPED OR SIMPLY SUPPORTED

NOTATION

A	= Area of cross section taken normal to the axis of revolution, in^2.
E	= Young's modulus, psi.
I_y, I_z	= Area moments of inertia taken about the y and z axes, respectively, in^4.
L	= Overall length of the cylinder, in.
M_x	= Running bending moment about middle surface of shell wall (see Figure 2), $\frac{\text{in-lb}}{\text{in}}$.
$\overline{M}_y$, $\overline{M}_z$	= Overall bending moments about the y and z axes, respectively (see Figure 2), in-lb.
$(\overline{M}_y)_A$, $(\overline{M}_z)_A$	= Artificial values for $\overline{M}_y$ and $\overline{M}_z$, respectively [see Equations (7)], in-lb.
$(\overline{M}_y)_B$, $(\overline{M}_z)_A$	= Artificial values for $\overline{M}_y$ and $\overline{M}_z$, respectively [see Equations (9)], in-lb.
$\overline{P}$	= Axial force (see Figure 1), lb.
$\overline{P}_A$	= Artificial value for $\overline{P}$ [see Equations (6)], lb.
$\overline{P}_B$	= Artificial value for $\overline{P}$ [see Equations (9)], lb.
R	= Radius of cylinder middle surface, in.
T	= Temperature change from that of an initial unstressed state or reference temperature (positive for a temperature rise), °F.
t	= Thickness of shell wall, in.
w	= Radial deflection of shell wall, in.
x, y, z	= Rectangular Cartesian coordinates (see Figure 1), in.
α	= Coefficient of linear thermal expansion, $\frac{\text{in}}{(\text{in})(°F)}$.

NOTATION*.

γ = Knock-down factor (see Figure 3), dimensionless.

ν = Poisson's ratio, dimensionless.

σ_A = Artificial axial stress defined by Equation (5), psi.

$\left(\sigma_{\bar{M}_y}\right)_B, \left(\sigma_{\bar{M}_z}\right)_B$ = Axial stresses due to the artificial bending moments $\left(\bar{M}_y\right)_B$ and $\left(\bar{M}_z\right)_B$, respectively, psi.

$\left(\sigma_{\bar{P}}\right)_B$ = Axial stress due to the artificial force $\bar{P}_B$, psi.

σ_x = Axial stress, psi.

$\left(\sigma_x\right)_{Max}$ = Peak value for σ_x, psi.

$\left(\sigma_x\right)_{cr}$ = Critical axial stress for buckling of the cylinder, psi.

ϕ = Angular coordinate (see Figure 1), radians.

Note: All stresses are positive in tension.

CONFIGURATION

The design curves and equations provided here apply only to thin-walled, right circular cylinders which satisfy the relationship

$$L/R \geq \frac{3.2}{\left(\frac{R}{t}\right)^{1/2}} \tag{1}$$

and are made of isotropic material. It is assumed that the shell wall is free of holes, obeys Hooke's law, and that it is of constant thickness. Figure 1 depicts the isotropic cylindrical shell configuration. Figure 2 shows the sign convention for forces, moments, and pressures.

BOUNDARY CONDITIONS

The following types of boundary conditions are covered:

a. Simply supported edge; that is,

$$w = M_x = 0 \quad \text{at } x = 0 \text{ and/or } x = L \tag{2}$$

b. Clamped edge; that is,

$$w = \frac{\partial w}{\partial x} = 0 \quad \text{at } x = 0 \text{ and/or } x = L \tag{3}$$

It is not required that the conditions at the two ends be the same. In every case, it is assumed that the cylinder (including any end rings) is not subjected to external axial constraints at any location around the boundaries at $x = 0$ and $x = L$.

TEMPERATURE DISTRIBUTION

The supposition is made that no thermal gradients exist through the wall thickness and in the axial direction. However, arbitrary circumferential variations may be present. The permissible distributions can therefore be expressed in the form

$$T = T(\phi) \tag{4}$$

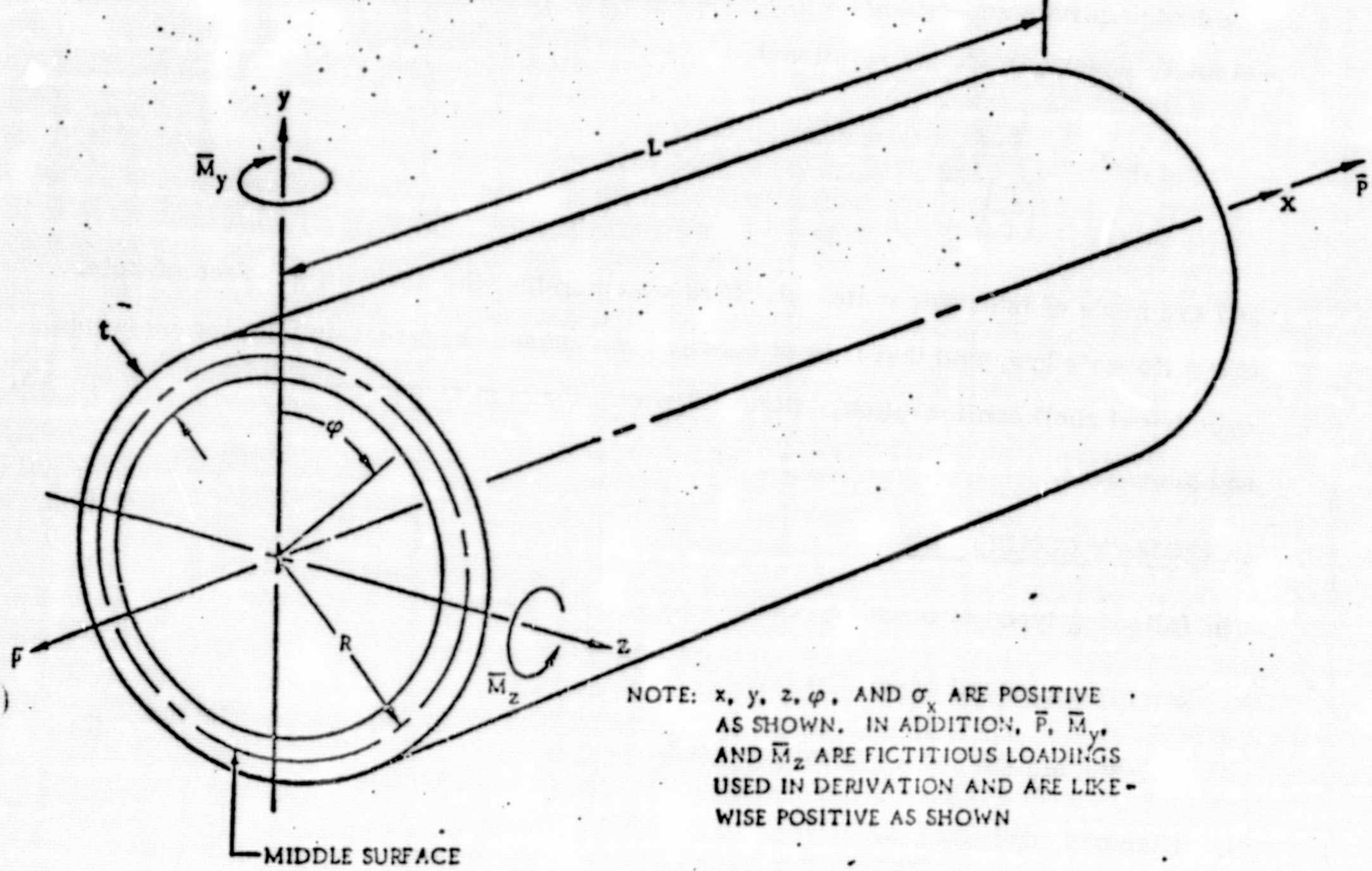


Figure 1. Isotropic Cylindrical Shell Configuration

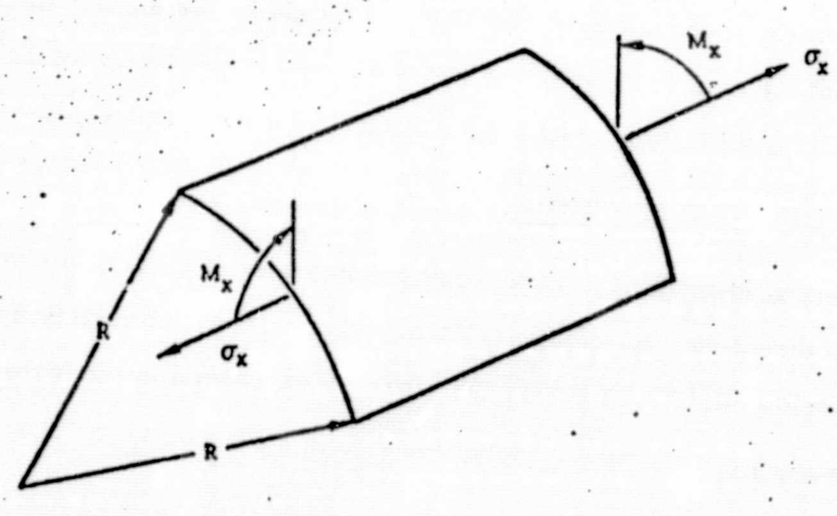


Figure 2. Sign Convention for Forces, Moments, and Pressure

Hoop membrane compression may develop in regions adjacent to the two ends due to external radial constraint. However, the buckling mode associated with this condition is not considered. Because of this and the lack of external axial constraints, the special case of a uniform temperature is of no interest here.

DESIGN CURVES AND EQUATIONS

It is assumed that Young's modulus and Poisson's ratio are unaffected by temperature changes. Hence, in using the contents of this TSN, the user must select effective values for each of these properties by applying engineering judgement. It will sometimes be desirable to employ different effective moduli in each of the following operations:

a. Computation of the stresses σ_x present in the cylinder.

b. Computation of the critical buckling stress $\left(\sigma_x\right)_{cr}$.

On the other hand, the results are presented in a form which enables the user to fully account for temperature-dependence of the thermal-expansion coefficient α.

The appropriate formulation for σ_x can be obtained by first imposing a fictitious stress distribution σ_A around the boundaries at $x = 0$ and $x = L$ such that all axial thermal deformations are entirely suppressed. It follows that

$$\sigma_A = -\alpha \bar{E} T(\phi) \tag{5}$$

These stresses may be integrated around the circumference and through the wall thickness to arrive at the force

$$\bar{P}_A = -EtR \int_0^{2\pi} \alpha T(\phi)\, d\phi \tag{6}$$

and the moments

$$\left(\bar{M}_y\right)_A = -ER^2 t \int_0^{2\pi} \alpha T(\phi) \sin\phi\, d\phi \tag{7}$$

$$\left(\overline{M}_z\right)_A = -ER^2t \int_0^{2\pi} \alpha T(\phi)\cos\phi \, d\phi \qquad (7) \text{ (Contd)}$$

Since it is assumed that the shell is free of external axial constraints, the conditions

$$\overline{P} = \overline{M}_y = \overline{M}_z = 0 \qquad (8)$$

must be satisfied at x = 0 and x = L. To restore the shell to such a state, it is necessary to superimpose a force $\overline{P}_B$ equal and opposite to $\overline{P}_A$ as well as moments $\left(\overline{M}_y\right)_B$ and $\left(\overline{M}_z\right)_B$ which are equal and opposite to $\left(\overline{M}_y\right)_A$ and $\left(\overline{M}_z\right)_A$, respectively. Hence,

$$\begin{aligned} \overline{P}_B &= -\overline{P}_A \\ \left(\overline{M}_y\right)_B &= -\left(\overline{M}_y\right)_A \\ \left(\overline{M}_z\right)_B &= -\left(\overline{M}_z\right)_A \end{aligned} \qquad (9)$$

The stress corresponding to $\overline{P}_B$ is easily found to be

$$\left(\sigma_{\overline{P}}\right)_B = \frac{\overline{P}_B}{A} = \frac{\overline{P}_B}{2\pi Rt} = \frac{E}{2\pi}\int_0^{2\pi} \alpha T(\phi)\, d\phi \qquad (10)$$

The stresses due to $\left(\overline{M}_y\right)_B$ are

$$\left(\sigma_{\overline{M}_y}\right)_B = \frac{\left(\overline{M}_y\right)_B z}{I_y} = \frac{\left(\overline{M}_y\right)_B z}{\pi R^3 t} = \frac{E\sin\phi}{\pi}\int_0^{2\pi} \alpha T(\phi)\sin\phi \, d\phi \qquad (11)$$

And those due to $\left(\overline{M}_z\right)_B$ are

$$\left(\sigma_{\overline{M}_z}\right)_B = \frac{\left(\overline{M}_z\right)_B y}{I_z} = \frac{\left(\overline{M}_z\right)_B y}{\pi R^3 t} = \frac{E\cos\phi}{\pi}\int_0^{2\pi} \alpha T(\phi)\cos\phi \, d\phi \qquad (12)$$

The procedure being used constitutes an application of Saint-Venant's principle. Hence, the stresses from Equations (10) through (12) will be accurate representations only at sufficient distances from the ends x = 0 and x = L. If end rings are present, the greater their resistance to out-of-plane bending, the shorter will be this distance. Subject to these conditions, the actual longitudinal thermal stresses at various points in the shell may be computed from the relationship

$$\sigma_x = \sigma_A + \left(\sigma_{\bar{P}}\right)_B + \left(\sigma_{\bar{M}_y}\right)_B + \left(\sigma_{\bar{M}_z}\right)_B \tag{13}$$

or,

$$\sigma_x = -\alpha E T(\phi) + \frac{E}{2\pi}\int_0^{2\pi} \alpha T(\phi)\, d\phi + \frac{E \sin\phi}{\pi}\int_0^{2\pi} \alpha T(\phi)\sin\phi\, d\phi$$

$$+ \frac{E \cos\phi}{\pi}\int_0^{2\pi} \alpha T(\phi)\cos\phi\, d\phi \tag{14}$$

Complex distributions may be encountered which make it difficult to perform the required integrations. In such instances, use can be made of numerical techniques whereby the integral signs are replaced by summation symbols.

To investigate the stability of a particular shell, the maximum longitudinal stress $\left(\sigma_x\right)_{Max}$ must be compared against the critical value which can be obtained from the formula

$$\left(\sigma_x\right)_{cr} = \gamma \frac{Et}{R\sqrt{3(1-\nu^2)}} \tag{15}$$

For the design to be satisfactory, it is required that

$$\left(\sigma_x\right)_{Max} < \left(\sigma_x\right)_{cr} \tag{16}$$

The quantity γ appearing above is a so-called knock-down factor which mainly accounts for the detrimental effects from initial imperfections. Note that Equation (15) is identical to that used for uniformly compressed circular, cylindrical shells. Its application to the present problem is justified on the basis of small-deflection studies reported in References 1 and 2. From the results given in these references, it can be concluded that, regardless of the nature of the circumferential stress distribution, classical theoretical instability is reached when the peak axial compressive stress satisfies the expression

$$\left(\sigma_x\right)_{Max} \approx \frac{Et}{R\sqrt{3(1-\nu^2)}} \tag{17}$$

In view of this, the values used here for γ were determined from the 99% probability (confidence = 0.95) data for uniformly compressed cylinders as reported in Reference 3. The resulting γ values are plotted in Figure 2 for $\frac{L}{R}$ ratios of 0.25, 1.0, and 4.0.

SUMMARY OF EQUATIONS AND CURVES

$$\sigma_x = -\alpha E T(\phi) + \frac{E}{2\pi}\int_0^{2\pi} \alpha T(\phi)\,d\phi + \frac{E \sin\phi}{\pi}\int_0^{2\pi} \alpha T(\phi) \sin\phi\, d\phi$$

$$+ \frac{E \cos\phi}{\pi}\int_0^{2\pi} \alpha T(\phi) \cos\phi\, d\phi \tag{18}$$

$$\left(\sigma_x\right)_{cr} = \gamma \frac{Et}{R\sqrt{3(1-\nu^2)}} \tag{19}$$

When $\nu = 0.3$ this gives

$$\left(\sigma_x\right)_{cr} = 0.606\,\gamma \frac{Et}{R} \tag{20}$$

The knock-down factor γ is obtained from Figure 3.

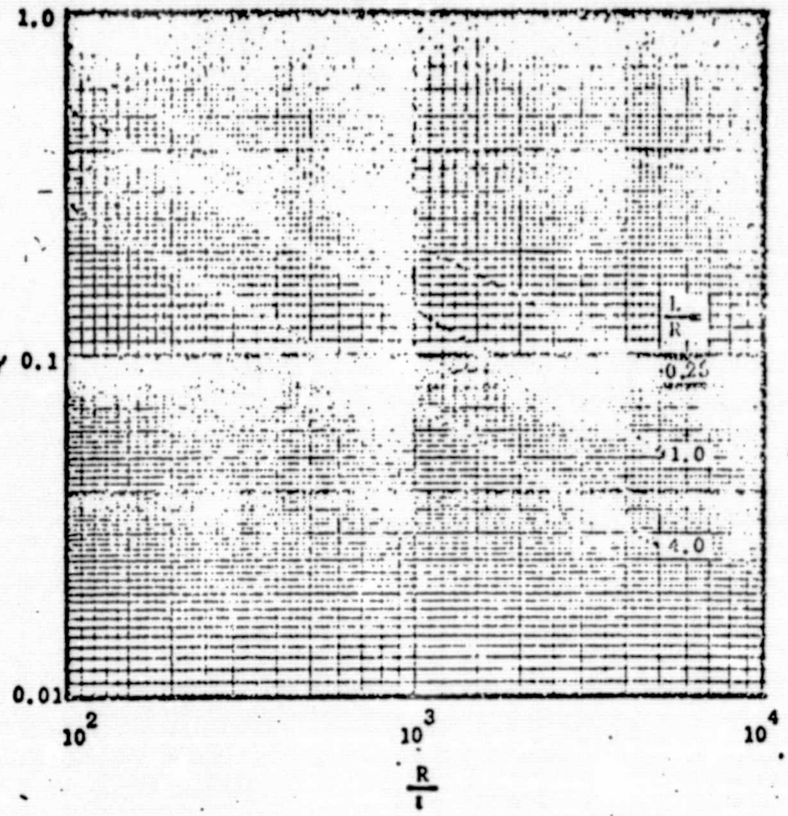


Figure 3. Knock-down Factor

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Estimated Thermal Stresses in Deep "T"

There will be some 19" high "T" rings in the LN_2 injection area of tunnel. Need to factor these into fatigue analysis.

Temperature Distribution

Both the insulation thickness and the "T" ring depth will be increased to 15". Therefore the resistance of the composite insulation will be increased approximately by a factor of 4. The deep "T" rings are located in a higher speed leg of the tunnel therefore the film coeff. will be higher. However, this will be a very small part of the total resistance and can be neglected. Therefore the overall heat loss will be reduced by a factor of 4, and it would be reasonable to assume that the temp. grad. in the deep "T" ($T_{flange} - T_{shell}$) will be the same as the small "T".

Heat loss thru "T".

$$Q_{DT} = \frac{KA}{t}(T_{flange} - T_{shell})$$

$$Q_{DT} = Q_{ST}/4 \qquad t_{DT} = 4\,t_{ST}$$

$$(T_f - T_s)_{DT} = \frac{Q_{ST}}{4}\,\frac{4t_{ST}}{KA} = (T_f - T_s)_{ST} = 10\,F^{\circ}$$

Thermal Stress

Use the results for the completely restrained shell:-

For $\Delta T = 10°$

	σ_L	σ_H
inside	-3000 *	500
outside	3000	2000

the shell geometry in the LN_2 region is similar to that for which curves were generated and will be good enough for estimates

$$* \ \sigma_L = \alpha E \Delta T = (10 \times 10^{-6})(30 \times 10^{6})(10°F)$$

$$\sigma_L = 3000 \text{ psi}$$